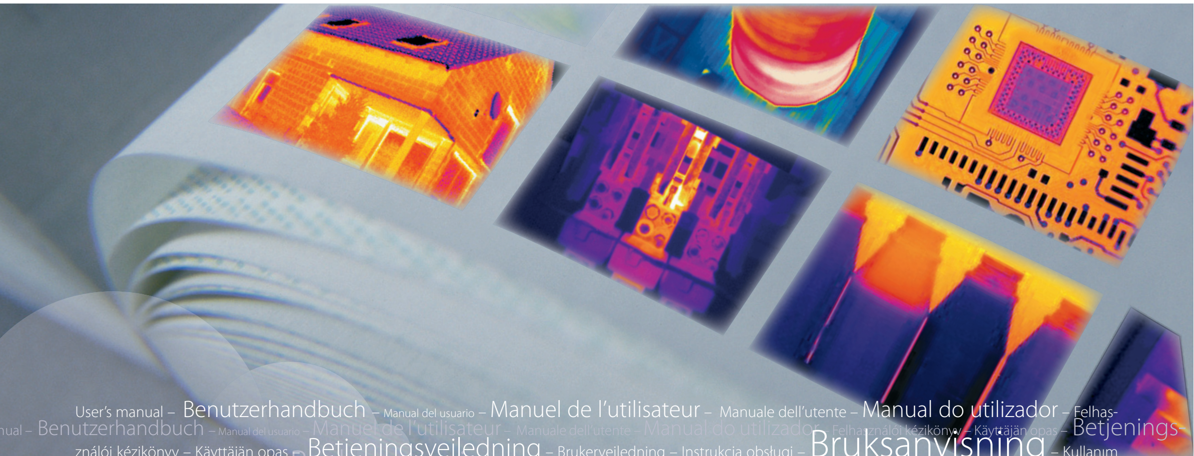
User’s manual



User’s manual – Benutzerhandbuch – Manual del usuario – Manuel de l’utilisateur – Manuale dell’utente – Manual do utilizador – Felhasználói kézikönyv – Käyttäjän opas – Betjeningsvejledning – Brukerveiledning – Instrukcja obsługi – Bruksanvisning – Kullanım Kılavuzu – Uživatelská příručka – Gebruikershandleiding

FLIR Reporter Building

Program version 1.1

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FLIR Reporter Building

User's manual

Publ. No. T559081 Rev. a348 – ENGLISH (EN) – June 8, 2009

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All products manufactured by FLIR Systems are warranted against defective materials and workmanship for a period of one (1) year from the delivery date of the original purchase, provided such products have been under normal storage, use and service, and in accordance with FLIR Systems instruction.

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The Quality Management System under which these products are developed and manufactured has been certified in accordance with the ISO 9001 standard.

FLIR Systems is committed to a policy of continuous development; therefore we reserve the right to make changes and improvements on any of the products described in this manual without prior notice.

Table of contents

1 Notice to user

Typographical conventions

This manual uses the following typographical conventions:

- **Semibold** is used for menu names, menu commands and labels, and buttons in dialog boxes.
- *Italic* is used for important information.
- `Monospace` is used for code samples.
- UPPER CASE is used for names on keys and buttons.

User-to-user forums

Exchange ideas, problems, and infrared solutions with fellow thermographers around the world in our user-to-user forums. To go to the forums, visit:

http://www.infraredtraining.com/community/boards/

Additional license information

This software is sold under a single user license. This license permits the user to install and use the software on any compatible computer provided the software is used on only one computer at a time. One (1) back-up copy of the software may also be made for archive purposes.

2 Customer help

General

For customer help, visit:

http://flir.custhelp.com

Submitting a question

To submit a question to the customer help team, you must be a registered user. It only takes a few minutes to register online. If you only want to search the knowledgebase for existing questions and answers, you do not need to be a registered user.

When you want to submit a question, make sure that you have the following information to hand:

- The camera model
- The camera serial number
- The communication protocol, or method, between the camera and your PC (for example, Ethernet, USB™, or FireWire™)
- Operating system on your PC
- Microsoft® Office version
- Full name, publication number, and revision number of the manual

Downloads

On the customer help site you can also download the following:

- Firmware updates for your infrared camera
- Program updates for your PC software
- User documentation
- Application stories
- Technical publications

3 Documentation updates

General

Our manuals are updated several times per year, and we also issue product-critical notifications of changes on a regular basis.

To access the latest manuals and notifications, go to the Download tab at:

http://flir.custhelp.com

It only takes a few minutes to register online. In the download area you will also find the latest releases of manuals for our other products, as well as manuals for our historical and obsolete products.

4 What is FLIR Reporter Building?

FLIR Reporter Building is a software package specifically designed to carry out advanced analyses of building structures.

You can use FLIR Reporter Building to analyze images that you have taken in the field with your infrared camera, and create inspection reports based on these images.

Examples of analyses that you can carry out include the following:

- detect humidity problems
- find insulation deficiencies
- calculate R and U values (For more information, refer to the white paper about R values on the Help menu.)
- estimate annual energy costs and savings
- find air infiltration
- work with data logging results
- easily and conveniently create professional-looking inspection reports
- analyze building structures, e.g. undertake a quantitative analysis of fastenings in insulation batts, calculate the necessary amount of building material to carry out a repair, or quantify insulation and humidity problems.

5 A note about training and applications

Infrared inspection of building structures – including infrared image and other data acquisition, analysis, diagnosis, prognosis, and reporting – is a highly advanced skill. It requires professional knowledge of thermography and of the building trade, and is, in some countries, subject to certification and legislation.

Consequently, we strongly recommend that you seek the necessary training before carrying out inspections. Please visit the following site for more information:

http://www.infraredtraining.com

The technique outlined in this manual has been successfully applied to light frame construction (stud frame walls, note 1 below) and studies are currently underway to validate usage on SIP construction (note 2 below) and concrete block wall construction (note 3 below). All tests were done in real-world conditions over a 24 hour period under semi-optimal conditions – no wind, no direct solar loading on the wall surfaces. Indoor air temperature kept as constant as heating system allowed. Outdoor air temperature varied several degrees. Preliminary results are promising for the latter construction types (note 2 and 3 below). Other types of walls have not yet been investigated, so FLIR Systems cannot document how well the technique will work with them.

1 4" stud wall with fiberglass batts and sheathing drywall both sides.
2 4" SIP (Structured Insulated Panel) construction with ¾ T&G (wood tongue & groove) inside and vinyl siding.
3 6" ICF (Insulated Concrete Form) with 2 ½" foam board on each side and drywall in, vinyl out.

6 Installation

6.1 System requirements

Operating system	■ Microsoft® Windows® XP with Service Pack 2 (SP2) ■ Microsoft® Windows® XP with Service Pack 3 (SP3) ■ Microsoft® Windows® Vista® with Service Pack 1 (SP1) **Note**: Run Windows® Update before you install FLIR Reporter Building.
Software	■ Microsoft® Office 2003 with Service Pack 3 (SP3), or ■ Microsoft® Office 2007 with Service Pack 1 (SP1) ■ An installed version 8.2 or later of FLIR Reporter.

Hardware	**Microsoft® Windows® XP:**
	■ Personal computer with an Intel® 800 MHz Pentium processor, or an AMD® Opteron, AMD® Athlon 64, or AMD® Athlon XP processor
	■ 512 MB of RAM (minimum)
	■ 20 GB of available hard disk space
	■ CD-ROM or DVD-ROM drive
	■ Super VGA (1024 × 768) or higher-resolution monitor
	■ Internet access required for web updates
	■ Keyboard and Microsoft® mouse, or a compatible pointing device
	
	Microsoft® Windows® Vista:
	■ Personal computer with a 1 GHz 32-bit (x86) processor
	■ 1 GB of RAM (minimum)
	■ 40 GB hard disk, with at least 15 GB available hard disk space
	■ DVD-ROM drive
	■ Support for DirectX® 9 graphics with:
	  ■ WDDM driver
	  ■ 128 MB of graphics memory (minimum)
	  ■ Pixel shader 2.0 in hardware
	  ■ 32 bits per pixel
	■ Super VGA (1024 × 768) or higher-resolution monitor
	■ Internet access (fees may apply)
	■ Audio output
	■ Keyboard and Microsoft® mouse, or a compatible pointing device

NOTE	■ Microsoft® Windows® XP 64-bit is not supported. ■ Microsoft® Windows® Vista 64-bit is not supported. ■ Actual requirements and product functionality may vary based on your system configuration.

6.2 Installation of FLIR Reporter Building

NOTE

- Installation may take up to 90 minutes, depending on the configuration of your computer.
- Customers buying FLIR Reporter Building as a separate product (i.e. not as a FLIR Reporter Building + FLIR Reporter software suite) will need a previous license for ThermaCAM™ Reporter/FLIR Reporter version 8.2 or later.
- Run Windows® Update before you install FLIR Reporter Building.

Procedure

Follow this procedure to install FLIR Reporter Building:

1	Close all running programs.
2	Insert the FLIR Reporter Building installation DVD into the DVD-ROM drive. The installation should start automatically. If the installation does *not* start automatically, follow this procedure: **1** Double-click **My Computer** on **Desktop**. **2** Right-click the CD-ROM drive and click **Explore**. **3** Locate and double-click SETUP.EXE.
3	Follow the on-screen instructions.
4	Restart the computer if you are asked to do so.
5	(In some cases the installation continues after the computer is restarted.)

7 Screen elements

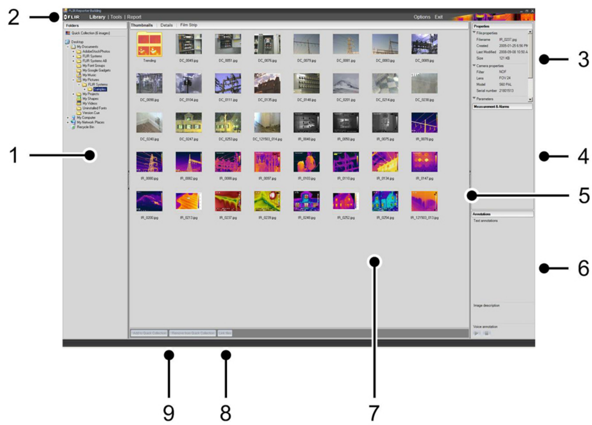
7.1 Organize tab

General

This section explains the screen elements on the **Organize** tab.

Figure

T630313;a2



Explanation

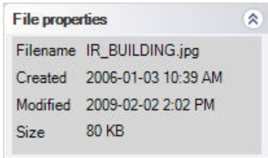
This table explains the figure above:

1	File explorer pane.
2	Main menu bar.
3	**Properties** pane. On this pane you can review the properties for a selected image, such as file properties, camera properties, and object parameters.
4	**Measurement and Alarms** pane. On this pane you can review the measurement and alarm results for a selected image.
5	Division lines to resize windows and panes.
6	**Annotations** pane. On this pane you can review and play back annotations, such as text annotations, image descriptions, voice annotations, etc.
7	Thumbnail view of the selected folder. You can also change this view to display the files in detail mode or filmstrip mode.
8	Button to link images.
9	Buttons to add images to and remove images from **Quick Collection**.

NOTE

You can expand/compress the right panes by clicking the arrows symbol. See the image below.

T630332;a2



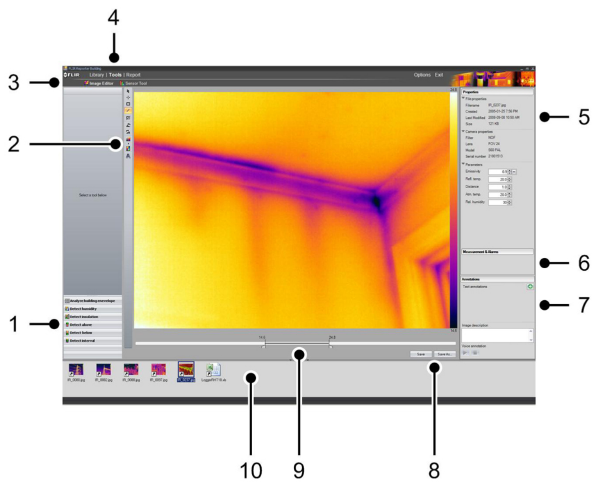
7.2 *Tools tab > Image Editor subtab*

General

This section explains the screen elements on the **Image Editor** subtab of the **Tools** tab.

Figure

T630314;a2



Explanation

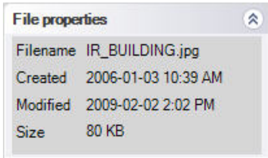
This table explains the figure above:

1	Measurement and analysis tools.
2	Main toolbar.
3	Submenu bar.
4	Main menu bar.
5	**Properties** pane. On this pane you can review the properties for a selected image, such as file properties, camera properties, and object parameters.
6	**Measurement and Alarms** pane. On this pane you can review the measurements and alarms results for a selected image.
7	**Annotations** pane. On this pane you can review, edit, and add text annotations and image descriptions, and play back voice annotations.
8	Button to save images after editing.
9	Controls to change the lower and upper temperature levels in the image.
10	Images pane.

NOTE

You can expand/compress the right panes by clicking the arrows symbol. See the image below.

T630332;a2



7.3 Tools tab > Panorama subtab

General

This section explains the screen elements on the **Panorama** subtab of the **Tools** tab.

Figure

T630378;a2

Explanation

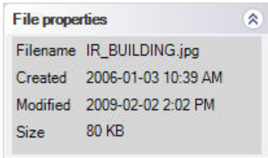
This table explains the figure above:

1	Submenu bar.
2	Main menu bar.
3	**File Properties** pane. On this pane you can review the file properties for a selected image.
4	**Camera Properties** pane. On this pane you can review the camera properties for a selected image.
5	Buttons to combine the images into a panorama image.
6	Images pane.

NOTE

You can expand/compress the right panes by clicking the arrows symbol. See the image below.

T630332;a2



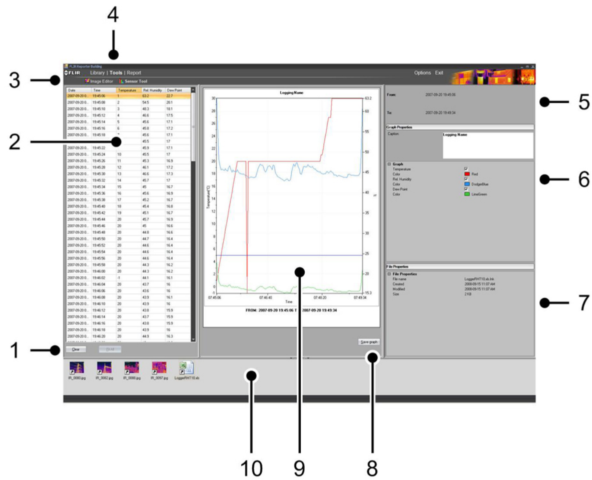
7.4 *Tools tab > Sensor Tool subtab*

General

This section explains the screen elements on the **Sensor Tool** subtab of the **Tools** tab.

Figure

T630315;a2



Explanation

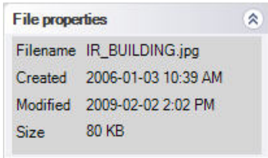
This table explains the figure above:

1	Button to select which range from the data logging to use.
2	Data logging source.
3	Submenu bar.
4	Main menu bar.
5	Data logging range.
6	**Graph Properties** pane. On this pane you can review and edit the properties for the currently displayed graph.
7	**File Properties** pane. On this pane you can review the properties for the currently displayed graph file.
8	Button to save the graph.
9	Plotted graph based on the data logging source.
10	Images pane. Here you will also find files that are used for the plotted graph.

NOTE

You can expand/compress the right panes by clicking the arrows symbol. See the image below.

T630332;a2



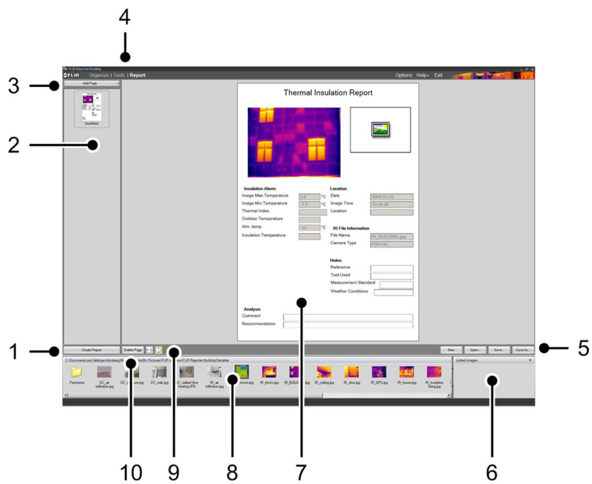
7.5 Report tab

General

This section explains the screen elements on the **Report** tab.

Figure

T630316;a2



Explanation

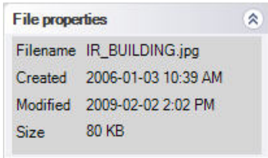
This table explains the figure above:

1	Button to create a report.
2	Thumbnail view of the report page.
3	**Add Page** button
4	Main menu bar.
5	Buttons to create new, save, and open existing reports (*.bsw).
6	**Linked images** pane.
7	Full view of the current report page.
8	Images pane.
9	Toolbar buttons to fit width and to fit height.
10	**Delete Page** toolbar button.

NOTE

You can expand/compress the right panes by clicking the arrows symbol. See the image below.

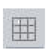
T630332;a2



7.6 Toolbar buttons on the **Tools** tab > **Image Editor** subtab

Explanation

This table explains the toolbar buttons on the **Tools** tab > **Image Editor** subtab.

	Select tool You use this tool when you want to move spots, areas, and lines within an image.
	Spotmeter tool You use this tool to create a spotmeter that you can put anywhere on the image. The spotmeter and the temperature it displays will be stored with the image when you save it. To move the spotmeter, use the Select tool to select the spotmeter tool, then click-drag the tool.
	Area tool You use this tool to click-and-drag within the image to create an area. The minimum and maximum temperatures in the area will be displayed in the measurement results table. To move the area, use the Select tool to select the area tool, then click-drag the tool.
	Line tool You use this tool to create a line within the image. The minimum and maximum temperatures along the line will be displayed in the measurement results table. To move the line, use the Select tool to select the line tool, then click-drag the tool.
	Grid tool You use this tool to create a grid on the image. You can set the grid properties using the **Grid settings** tool. The grid will not be stored with the image when you save it. **Note:** The grid tool has on/off functionality. You need to click the toolbar button to disable the tool.
	Show/hide overlay graphics tool. You use this tool to display and hide the overlay graphics that are associated with the image from the infrared camera.
	Rotate counter-clockwise tool You use this tool to rotate an image counter-clockwise in 90° increments.
	Rotate clockwise tool You use this tool to rotate an image clockwise in 90° increments.

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	Palette tool You use this tool to change the color palette within an image.
	Invert palette tool You use this tool to invert the currently selected palette.
	Auto-adjust tool You use this tool to auto-adjust an image for the optimum brightness and contrast.
	Fit width tool You use this tool to resize the image to fit the width of the image window.
	Fit height tool You use this tool to resize the image to fit the width of the image window.

8 Workflow

General

When you use FLIR Reporter Building, you follow a standard workflow. This workflow is implemented in the software package and is explained in this section.

Workflow

This table explains the workflow:

1	At the inspection site, carry out your infrared inspection. Take advantage of the features in your infrared camera, such as analysis tools, text annotations, voice annotations, etc. At this point, you have also the choice of using additional tools, such as temperature and humidity data loggers.
2	Move your images from the camera to a location of your choice on your computer, using the memory card or a USB cable.
3	Start FLIR Reporter Building.
4	On the **Organize** tab, choose the images that you want to work with.
5	On the **Tools** tab, perform the anayses of your choice. You can detect humidity, detect insulation deficiencies, add spotmeters, areas, lines, and more. Here you can also stitch together normal images into larger panorama images (vertical or horizontal).
6	On the **Report** tab, prepare the report by choosing from a variety of page templates, then moving your images into your report using a drag-and-drop operation.
7	On the **Report** tab, click **Create Report**. This will open FLIR Reporter and create the report as a Microsoft® Word document.

SEE

For more information, see the following sections:

- Section 9 – Choosing and linking images on page 21
- Section 10 – Using the tools on page 25
- Section 11 – Creating the report on page 39

9 Choosing and linking images

General

You can choose images and files using one of two different methods:

- Choosing images and files using the file explorer pane. Using this method you can only work with images and files in one folder at a time.
- Choosing images and files using **Quick Collection**. Using this method, you can choose images and files from several different locations in the file explorer, and add these images and files to a collection. It is then that collection of images and files that you work with.

You can also link, i.e. associate, two images to each other. A situation when you would want to link images is, for example, associating a digital photo with an infrared image.

SEE

For more information, see the following sections:

- Section 9.1 – Choosing images and files using the file explorer pane on page 22
- Section 9.2 – Choosing images and files using Quick Collection on page 23
- Section 9.3 – Linking images on page 24

9.1 Choosing images and files using the file explorer pane

General

This section describes how you choose images and files using the file explorer pane. Using this method you can only work with images and files in one folder at a time.

Procedure

Follow this procedure to choose images and files using the file explorer pane:

1	On the main menu bar, click the **Organize** tab.
2	In the file explorer pane, select the folder or storage device where you have put your images and files. The images and files will now be displayed as thumbnails or in the detail view in the middle pane.

9.2 Choosing images and files using **Quick Collection**

General

This section describes how you choose images and files using **Quick Collection**.

You can think of the **Quick Collection** as a temporary workspace. The images and files you add to the **Quick Collection** are essentially shortcuts to their original locations, and this lets you add images and files from several different locations, such as your local hard disk drive, external storage devices, etc.

This also means that if you delete an image or a file from its original location, it will also be deleted from the **Quick Collection**.

Procedure

Follow this procedure to choose images and files using **Quick Collection**:

1	On the main menu bar, click the **Organize** tab.
2	In the file explorer pane, go to the folders or storage devices where you have put your images and files.
3	In the middle pane, select the images and files that you want to add to your collection.
4	Click **Add to Quick Collection** to add the images and files to the collection.
5	Repeat Steps 2–4 for all folders and storage devices containing images and files that you want to add to your collection.

NOTE

- When you are ready to analyze your images and files, make sure that you click **Quick Collection** at the top of the file explorer pane before clicking the **Tools** tab.
- To remove images and files from the **Quick Collection**, click **Remove from Quick Collection**.
- Images and files added to the **Quick Collection** will stay there between program sessions.

9.3 Linking images

General

This section describes how you link two images. Linking images simplifies organizing and makes it easier to drag-and-drop the images onto the report pages.

Procedure

Follow this procedure to link two images:

1	Choose your images according to the procedures in section 9.1 – Choosing images and files using the file explorer pane on page 22 or section 9.2 – Choosing images and files using Quick Collection on page 23.
3	Select two images, and click **Link files**. The images are now linked. On the **Report** tab, when you select an image to which an image is linked, the linked image will be displayed in the **Linked images** pane at the bottom of the screen

NOTE

Some infrared cameras support linking, so images may already be linked when they are imported from the camera.

10 Using the tools

10.1 Laying out a spotmeter, an area, or a line

General

This section describes how you lay out a spotmeter, an area, or a line.

Procedure

Follow this procedure to lay out a spotmeter, an area, or a line:

1	On the main menu bar, click **Tools** > **Image Editor**.
2	In the Images pane at the bottom, click the image you want to work with.
3	On the main toolbar, click one of the following toolbar buttons: ■ Spotmeter toolbar button:  ■ Area toolbar button:  ■ Line toolbar button: 
4	On the image, click where you want to place the spotmeter, or click and drag to lay out the area or the line. The measurement results will now be displayed in the **Measurement and Alarms** pane to the right.

SEE

For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.

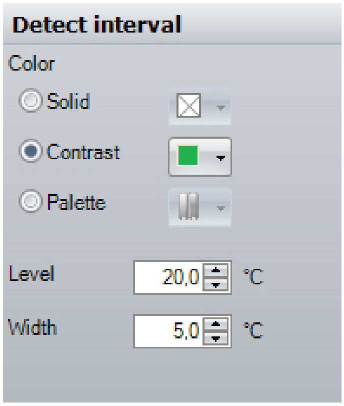
10.2 Detecting a temperature interval

General

This section describes how you detect all areas within a set temperature interval in an infrared image.

Figure

T638032;a1



Procedure

Follow this procedure to detect all areas within a set temperature interval in an infrared image:

1	On the main menu bar, click **Tools**.
2	In the Images pane, click the image you want to work with.
3	Click **Detect interval**.
4	Select a temperature level.
5	Select a temperature width.
6	Select an isotherm color. The isotherm color will now cover all areas within the temperature width and above the set temperature level. You can choose between three different types of isotherm colors: ■ **Solid** ■ **Contrast** ■ **Palette** You will need to test different settings to see which type is the most suitable for your application.

NOTE

When you change a value, you can also change it by click-dragging the value's label. See the figure below.

T630333;a1

SEE

- For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.
- For an explanation of isotherms, see section 15 – Glossary on page 100.

10.3 Detecting a temperature below a set temperature

General

This section describes how you detect all areas below a set temperature level in an infrared image.

Procedure

Follow this procedure to detect all areas below a set temperature level in an infrared image:

1	On the main menu bar, click **Tools**.
2	In the Images pane, click the image you want to work with.
3	Click **Detect below**.
4	Select a temperature level.
5	Select an isotherm color. The isotherm color will now cover all areas below the set temperature level. You can choose between three different types of isotherm colors: ▪ **Solid** ▪ **Contrast** ▪ **Palette** You will need to test different settings to see which type is the most suitable for your application.

NOTE

When you change a value, you can also change it by click-dragging the value's label. See the figure below.

T630333;a1

SEE

- For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.
- For an explanation of isotherms, see section 15 – Glossary on page 100.

10.4 Detecting a temperature above a set temperature

General

This section describes how you detect all areas above a set temperature level in an infrared image.

Procedure

Follow this procedure to detect all areas above a set temperature level in an infrared image:

1	On the main menu bar, click **Tools**.
2	In the Images pane, click the image you want to work with.
3	Click **Detect above**.
4	Select a temperature level.
5	Select an isotherm color. The isotherm color will now cover all areas above the set temperature level. You can choose between three different types of isotherm colors: ■ **Solid** ■ **Contrast** ■ **Palette** You will need to test different settings to see which type is the most suitable for your application.

NOTE

When you change a value, you can also change it by click-dragging the value's label. See the figure below.

T630333;a1

SEE

- For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.
- For an explanation of isotherms, see section 15 – Glossary on page 100.

10.5 Detecting an insulation deficiency

General

The **Detect insulation** tool can detect areas where there may be an insulation deficiency in the building. It will trigger when the thermal index falls below a preset value of the energy leakage through a wall.

Different building codes recommend different values for the thermal index, but typical values are 60–80% for new buildings. Refer to your national building code for recommendations.

Procedure

Follow this procedure to detect an insulation deficiency:

1	On the main menu bar, click **Tools**.
2	In the Images pane, click the image you want to work with.
3	Click **Detect insulation**.
4	Select an isotherm color. You can choose between three different types of isotherm colors: ■ **Solid** ■ **Contrast** ■ **Palette** You will need to test different settings to see which type is the most suitable for your application.
5	Select values for the following: ■ Indoor temperature (recorded at the time of inspection). ■ Outdoor temperature (recorded at the time of inspection). ■ Thermal index (see discussion above, refer to your national building code for recommendations). The alarm temperature will now be calculated, and the isotherm color will mark the areas suspectible to an insulation deficiency.

NOTE

When you change a value, you can also change it by click-dragging the value's label. See the figure below.

T630333;a1

SEE

- For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.
- For an explanation of isotherms, see section 15 – Glossary on page 100.

10.6 Detecting a humidity problem

General

The **Detect humidity** tool can detect areas suspectible to a humidity problem. If you use this tool, and set the relative humidity level to 100%, you will detect areas where there is a risk of humidity resulting in the condensation of liquid water, i.e. the dewpoint temperature.

However, depending on the building materials and the presence of organic matter, humidity levels as low as 70% can provide sufficient moisture for mold to grow. To detect these areas, set a lower relative humidity level.

Procedure

Follow this procedure to detect humidity:

1	On the main menu bar, click **Tools**.
2	In the Images pane, click the image you want to work with.
3	Click **Detect humidity**.
4	Select an isotherm color. You can choose between three different types of isotherm colors: ▪ **Solid** ▪ **Contrast** ▪ **Palette** You will need to test different settings to see which type is the most suitable for your application.
5	Select values for the following: ▪ Relative humidity (recorded at the time of inspection). ▪ Relative humidity level (see discussion above). ▪ Atmospheric temperature (recorded at the time of inspection). The alarm temperature will now be calculated, and the isotherm color will mark the areas suspectible to a humidity problem.

NOTE

When you change a value, you can also change it by click-dragging the value's label. See the figure below.

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SEE

- For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.
- For an explanation of isotherms, see section 15 – Glossary on page 100.

10.7 Analyzing building structures using the **Grid settings** tools

General

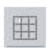
Using the **Grid settings** tool, and knowing the field of view of the lens and the distance to the object of interest, you can lay out a grid on an image where each square of the grid represents a known area.

You can then use the **Grid settings** tool for a variety of different tasks, such as:

- A quantitative analysis of fastenings in insulation batts.
- Calculating the necessary amount of building material to carry out a repair.
- Quantifying insulation and humidity problems.

Procedure

Follow this procedure to prepare an analysis of the building structure:

1	On the main menu bar, click **Tools**.
2	In the Images pane, click the image you want to work with.
3	Click **Grid settings**.
4	Do one of the following: ■ Select values for the distance and field of view. ■ Lay out a line using the  toolbar button, then select the line in the **Line** box and specify the line length.
5	Click the  toolbar button in the main toolbar to enable the grid.
6	Set the grid size to a value of your choice.
7	Select the  toolbar button, and move the grid to the desired position. For example, you may want to align it with certain structures in the image, areas of interest, etc.
8	Select **Linked images** to lock the grid relative to the images.
9	Depending on your workflow, you may now want to do one of the following: ■ Leave the grid as is, and begin counting fastenings, calculating the amount of necessary building material, etc. ■ Convert grid areas to measurement areas in order to quantify insulation and humidity problems. To do that, click in a grid area of your choice, then click the  toolbar button. In the right pane you can now see that a measurement area has been created

NOTE

- For an accurate calculation, it is very important that you record the correct distance to the object at the time of inspection. You can do this in the camera, or on paper.
- For an accurate calculation, it is very important that the image is taken at a 90° angle to the object (e.g. the wall).

- When you change a value, you can also change it by click-dragging the value's label. See the figure below.

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SEE

For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.

10.8 Using the sensor tool

General

You can include data from data loggers in your report.

The user scenario suggests using an Extech RHT10 Humidity and Temperature USB Data Logger or Extech TH10 Temperature USB Data Logger, but other data loggers capable of outputting the same data in Microsoft® Excel format are suitable (see section 10.8.1 – Structure of the data logger file on page 35 for more information).

Procedure

Follow this procedure to create a graph based on the logging data:

1	Add the Microsoft® Excel file to your collection by following the procedure in section 9.2 – Choosing images and files using Quick Collection on page 23.
2	On the main menu bar, click **Tools**, then click **Sensor Tool**.
3	Move the Microsoft® Excel file from the Images pane to the left pane using a drag-and-drop operation. This will display the data in tabular form. A graph of the data will be displayed in the middle pane.
4	If you want to limit the data, you can do so by click-dragging the table at the top or at the bottom. An arrow on the graph shows the data that will be trimmed.
5	If you want to review or edit the graph properties and file properties, you can do so in the right pane.
6	To save the graph as an image, click **Save** and save the image to a location of your choice.
7	You can now include the graph as an image in your report by following the procedure in section 11 – Creating the report on page 39.

SEE

For an introduction to building thermography, see section 13 – Introduction to building thermography on page 51.

10.8.1 Structure of the data logger file

Figure

This figure shows the structure of the data logger file from an Extech RHT10 Humidity and Temperature USB Data Logger and an Extech TH10 Temperature USB Data Logger:

T630331;a1

	A	B	C	D	E	F	G
1	>>Logging Name:Logging Name						
2	>>FROM:09-20-2007 19:45:06 TO:09-20-2007 19:49:34						
3	>>Sample Points:135						
4	>>Sample Rate:2 sec.						
5	>>Temperature Unit:Celsius						
6	>>Temperature(LowAlarm:20.0-HighAlarm:22.0) Relative Humidity(LowAlarm:30.0-Hig						
7	--						
8	NO.	DATE	TIME	TEMPERATURE	RELATIVE	DEW-POINT	
9	1	2007-09-20	19:45:06	1.00	63.2	22.7	
10	2	2007-09-20	19:45:08	2.00	54.5	20.1	
11	3	2007-09-20	19:45:10	3.00	48.3	18.1	
12	4	2007-09-20	19:45:12	4.00	46.6	17.5	
13	5	2007-09-20	19:45:14	5.00	45.6	17.1	
14	6	2007-09-20	19:45:16	6.00	45.8	17.2	
15	7	2007-09-20	19:45:18	7.00	45.6	17.1	
16	8	2007-09-20	19:45:20	8.00	45.5	17	
17	9	2007-09-20	19:45:22	9.00	45.9	17.1	
18	10	2007-09-20	19:45:24	10.00	45.5	17	
19	11	2007-09-20	19:45:26	11.00	45.3	16.9	
20	12	2007-09-20	19:45:28	12.00	46.1	17.2	
21	13	2007-09-20	19:45:30	13.00	46.6	17.3	
22	14	2007-09-20	19:45:32	14.00	45.7	17	
23	15	2007-09-20	19:45:34	15.00	45	16.7	
24	16	2007-09-20	19:45:36	16.00	45.6	16.9	
25	17	2007-09-20	19:45:38	17.00	45.2	16.7	
26	18	2007-09-20	19:45:40	18.00	45.4	16.8	
27	19	2007-09-20	19:45:42	19.00	45.1	16.7	
28	20	2007-09-20	19:45:44	20.00	45.7	16.9	
29							

10.9 *Zooming into or out of images*

General

You can zoom into or out of images on the **Tools** tab.

Procedure

To zoom into an image, do one of the following:

- ALT + left mouse button down
- SHIFT + SCROLL button (zoom in, zoom out)
- SHIFT + left mouse button down (move the zoomed area)

To reset the zoom factor, do one of the following:

- Click the  toolbar button.
- Click the  toolbar button.

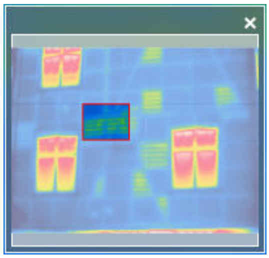
10.10 Panning over images

General

You can pan over images using the image navigator.

Procedure

Follow this procedure to pan over images:

1	On the **Tools** tab, click the  toolbar button in the bottom right corner of the image. The toolbar button is normally hidden, but will be displayed when you hover over it with the cursor. This will display an image navigator of the following shape: T630334;a2 
2	In the image navigator, click-drag the zoomed-in area to pan over the image.

*10.11 Using the **Panorama** tool*

General

Some cameras from FLIR Systems support taking several smaller images that later can be stitched together into one large image.

This feature is called **Panorama**. FLIR Reporter Building is one of the programs in which you can carry out the actual combining of the images. This procedure shows how.

Procedure

Follow this procedure:

1	On the **Organize** tab, go to the folder where you keep the images that you want to combine into a larger image.
2	(Optional:) Add the images to the Quick Collection.
3	Go to the **Tools** tab and select **Panorama**.
4	In the film strip view, select one of the tagged images, and wait until all the associated images are displayed in the image window. The image window will now display all the associated images in the same sequence in which they were taken by the camera (either horizontally or vertically, depending on how they were taken).
5	Click the **Combine** button. The images are now stitched together into a larger image.
6	Once the operation is complete, you can save the large image to any location by clicking **Save**. You can also see the individual images by moving the mouse cursor on the top of the large image.
7	Go to the **Tools** tab > **Image Editor** tab to carry out futher analysis of the image.

11 Creating the report

General

When you have finished the analyses of your images, you can now create the report. This section describes how you create the report by choosing one or more predefined report template pages.

Figure

This figure shows the predefined report template pages:

T630327;a2

Procedure

Follow this procedure to create a report:

1	On the main menu bar, click **Report**.
2	At the top of the left pane, click **Add Page** and select one of the predefined report template pages. You can choose from the following types of pages: ▪ **General** ▪ **Air Tightness** pages ▪ **Humidity** pages ▪ **Insulation** pages A thumbnail view of your report pages will be displayed in the left pane.
3	In the left pane, click the thumbnail of the report page that you want to work with. This will display the report page in the middle pane.
4	From the Images pane at the bottom of the screen, move images onto the report page, using a drag-and-drop operation. As you will see, a number of fields on the report page will be populated by the information that is stored inside the image files. In other fields you can add information by simply typing text in the field. On some report pages, you can also update the calculated output values by changing the input values.
5	Repeat Steps 2–4 until you have added as many report pages and images as you want in your report. If you want to change the page order, you can do so by moving the report pages in the left pane.

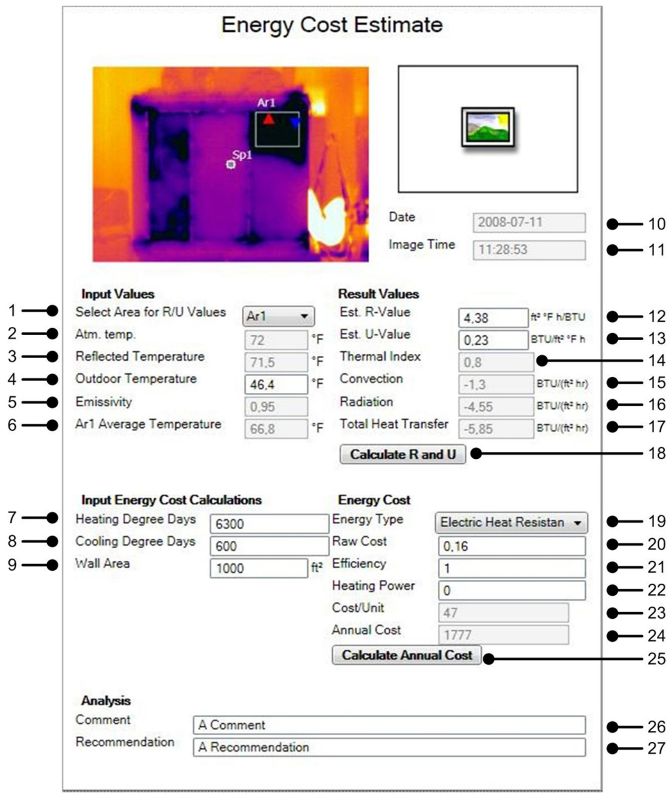
6	Do one of the following: ▪ To create the report immediately, click **Create Report**. This will open FLIR Reporter and create the report as a Microsoft® Word document. Creating a report may take several minutes, depending on its complexity. ▪ To save the report in an intermediate report format (*.bsw), click **Save As** and save the report to a location of your choice. You can then open the intermediate report file again at a later time and continue working on it.

11.1 Understanding the *Energy Cost* report template

11.1.1 Explanation of the template

Figure

T630393;a1



Explanation

This table explains the figure above:

1	Drop-down menu to select the area on which the calculation shall be based.
2	**Atm. temp.**: The temperature of the atmosphere between the camera and the target
3	**Reflected Temperature**. This parameter is used to compensate for the radiation reflected by the object. If the emissivity is low and the object temperature relatively far from that of the reflected temperature, it will be important to set and compensate for the reflected apparent temperature correctly.

4	**Outdoor Temperature**: The temperature outside the building.
5	**Emissivity**: The most important object parameter to set correctly is the emissivity, which, in brief, is a measure of how much radiation is emitted from the object, compared with that from a perfect blackbody of the same temperature.
6	**Average Temperature**: The average temperature in the area defined in callout 1 above.
7	**Heating Degree Days**: A quantitative index designed to reflect the demand for energy needed to heat a home or business. For more information, see http://en.wikipedia.org/wiki/Heating_degree_day
8	**Cooling Degree Days**: A quantitative index designed to reflect the demand for energy needed to cool a home or business. For more information, see http://en.wikipedia.org/wiki/Heating_degree_day
9	**Wall Area**: This is the total area in the wall of similar structure as the selected area in the infrared image. The entire wall does not have to have the same structure.
10	**Date**: The date when the report is generated.
11	**Image Time**: The time when the image was taken.
12	**Est. R-value**: The result of the calculation as an esitmated R value.
13	**Est. U-value**: The result of the calculation as an esitmated U value.
14	**Thermal index**: The insulation level in the wall. Different building codes recommend different values for the thermal index, but typical values are 0.6–0.8 for new buildings. Refer to your national building code for recommendations.
15	**Convection**: A calculated estimated value, indicating the heat transfer as convection.
16	**Radiation**: A calculated estimated value, indicating the heat transfer as radiation.
17	**Total Heat Transfer**: The total heat transfer, including both convection and radiation.
18	**Calculate R and U**: Button to update the calculation if any input data have been changed.

19	**Energy Type**: How the building is heated. Options include: ■ **Electric Heat Pump** ■ **Electric Heat Resistance** ■ **Fuel Oil** ■ **Hardwood** ■ **Natural Gas** ■ **Propane**
20	**Raw Cost**: The raw cost of the selected energy type. See the White paper on R values on the **Help** menu for more information.
21	**Efficiency**: The efficiency of the selected energy type. See the White paper on R values on the **Help** menu for more information.
22	**Heating Power**: See the White paper on R values on the **Help** menu for more information.
23	**Cost/Unit**: The cost per unit of the selected energy type. See the White paper on R values on the **Help** menu for more information.
24	**Annual cost**: The annual cost of the selected energy type. See the White paper on R values on the **Help** menu for more information.
25	**Calculate Annual Cost**: Button to update the calculation if any energy type input data have been changed.
26	**Comment**: If an infrared image has a text annotation, and the text annotation has a label Comment, the value of that label will populate this field.
27	**Recommendation**: If an infrared image has a text annotation, and the text annotation has a label Recommendation, the value of that label will populate this field.

11.1.2 Formulas used for calculations

General

This table lists the formulas that are used in the template. The numbers in the left column refer to corresponding parameters in the previous section.

Formulas

12	**Est. R-value**: ▪ `EstRValue = (IndoorTemperature – OutdoorTemperature)/(RadiativeLossEstimate + ConvectiveLossEstimate)` ▪ `AmericanEstRValue: 5.678269 × MetricEstRValue`
13	**Est. U-value**: ▪ `1/EstRValue`
14	**Thermal index**: ▪ `ThermalIndex = (WallSurfaceTemperature – OutdoorTemperature)/(IndoorTemperature – OutdoorTemperature)`
15	**Convection**: ▪ Calculated according to Eq. 2 in White paper on R values on the **Help** menu.
16	**Radiation**: ▪ Calculated according to Eq. 3 in White paper on R values on the **Help** menu.
23	**Cost/Unit**: ▪ `CostPerUnit = RawCost/(Efficiency × HeatingPower)`
24	**Annual cost**: ▪ `AnnualCost = CostPerUnit × EnergyConsumption` (where `EnergyConsumption` is calculated using Eq. 5 and 6 in White paper on R values).

12 Excerpts from whitepaper on R-values

Note: The complete whitepaper is available on the **Help** menu in FLIR Reporter Building.

12.1 About the author

Robert P. Madding, Director, ITC, FLIR Systems, Inc.

Bob is a graduate of the University of Missouri with a BS in Physics, and a Masters and Ph.D. in Physics from the University of Wisconsin-Madison. He began the first infrared thermography seminar at the University of Wisconsin Extension (UWEX) in 1978. At the UWEX he worked with colleagues to develop the first residential and commercial building energy audit programs and courses. In 2000 he founded the Inframation Conference, the largest annual IR conference for thermographers. He has published numerous technical papers on infrared thermography applications, as well as contributing chapters to textbooks such as Applied Thermal Design and the Encyclopedia of Optical Engineering. Bob has over 25 years experience in infrared thermography applications and training.

12.2 General

One can calculate the R-Value for an exterior wall segment by estimating the heat flow between the interior of a room and the interior wall surface. In steady state heat transfer conditions, all the heat that flows to the wall flows through the wall. Quantifying the heat flow through the “air film” near the surface of the wall is a straightforward radiation and convection calculation. One needs to know the indoor, outdoor, wall surface and reflected temperatures and the wall emissivity. One does not need to know the wall construction. The challenge is, especially for well insulated walls, that the difference in temperature between the room and wall surface can be small, sometimes only a degree or two, sometimes even less. Calculations based on small delta-T’s can result in large errors.

For steady state conditions and proper measurement, the R-Value should remain constant. Measurement uncertainties were using the Standard Deviation to Average Value ratio for various measurement techniques and weather conditions.

Insulation retrofits cost money and one could reasonably ask what the cost benefit ratio is for doing this. To this end the author has developed an algorithm that estimates the R-Value of a wall section, then estimates savings in energy cost by improving the

insulation level to a higher value. The user has control over the input variables, including R-values, energy costs, efficiencies, affected area and degree days. Uncertainties exist at every turn, so the estimates aren't going to be to the nearest dollar, but should give a reasonable guideline. The algorithm only does insulation retrofit. It does not include air infiltration/exfiltration effects which can be 30% to 70% of the heat loss, lifestyle effects, extreme weather conditions beyond recorded historical averages and so on.

12.3 R-value measurement

R-Value is the resistance to heat flow for a building element. Insulating materials are rated in R-Value in the U.S. and other countries. The higher the R-Value, the better the insulating material. Many countries also use the reciprocal of R-Value, called U-Value. U=1/R.In steady state conductive heat flow through an area such as that depicted in Figure 1, R-Value is given by equation 1 where A is the surface area the heat Q is flowing through driven by temperature difference between inside air and outside air, ΔT_{io} (Eq. 1):

$$R - Value = \frac{A\Delta T_{io}}{Q}$$

Steady state heat flow through the internal air film is by convection and radiation. The classic Stefan-Boltzmann radiative heat transfer equation that varies as the fourth power of the high temperature minus the fourth power of the low temperature ($T_{hi}^4 – T_{lo}^4$) can be well approximated in our case by a simpler equation where the emissivity, ε, Stefan-Boltzmann constant, σ, and absolute average temperature cubed, T_m^3 all multiply ΔT_r, the temperature difference between the wall surface (low temperature in heating season) and the inner room surface temperatures also called reflected apparent temperature (high temperature in heating season) (Eq. 2):

$$Q_{rad} = 4\varepsilon\sigma A T_m^3 \Delta T_r$$

Unity view factor is assumed, meaning the surface we're viewing "sees" all other surfaces equally at temperature T_{rat}, the reflected apparent temperature. This is a good approximation when measuring indoors as most of the surfaces surrounding an outside wall will be nearly the same temperature. From the outside, a different scenario is seen as a clear sky can be -60°F, making the view factor equal one approximation inaccurate. The author strongly recommends performing these measurements from the inside during the heating season for this and other reasons such as accessibility and better control of other environmental parameters.

Heat transfer by convection is given by (Eq. 3):

$$Q_{conv} = h_c A \Delta T_a$$

where h_c is the convective coefficient and ΔT_a the temperature difference between the wall surface and bulk room air temperature. The value of h_c depends on several factors including the wall height and room air temperature. For tall walls and large ΔT_a, one can have turbulent flow which is a different h_c from laminar flow. There are different values of h_c given by different references. Units of Q are BTU/hr or Watts. Substituting into Eq. 1 results in an equation with known constants and measurable variables (Eq. 4):

$$R - Value = \frac{\Delta T_{io}}{4\varepsilon\sigma T_m^3 \Delta T_r + h_c \Delta T_a}$$

One needs to know the temperature difference between the wall surface and inside air, ΔT_a, between wall surface and reflected apparent temperature, ΔT_r, and between inside air and outside air temperatures, ΔT_{io}. One also needs a mean temperature, T_m and a characteristic length for determining h_c. The IR camera plays a key role here as thermal uniformity of wall surfaces is not realized in many cases. Example cases will show this clearly.

Temperature differences such as ΔT_a and ΔT_r can be as small as 0.5°F for well insulated walls and low ΔT_{io} and over 10°F for poorly insulated walls and high ΔT_{io}. How can one hope to get decent measurements with such small temperature differences using IR cameras with accuracy specifications of ±2°C (±3.6°F)? This is possible as temperature differences are the primary measurements. IR camera accuracy specifications include both random and systematic errors for absolute temperature measurement. By measuring all the temperature differences with the same device (the IR camera) at the same time and in the same image, one avoids systematic error and need focus only on random error.

For IR cameras random error is associated with NETD, noise equivalent temperature difference, typically given in the IR camera specifications. Very good NETD is 40 mK (For temperature differences, milliKelvin is the same as milliCelsius. Multiply by 1.8 to convert mK to mF, milliFahrenheit. Divide by 1000 to get the actual temperature difference in Fahrenheit degrees, such as 0.072°F.) So-so NETD is 100 mK and not very good NETD is 200 mK. The uncertainty analysis section shows that it takes a very good NETD to get decent measurements on well insulated areas even with moderate ΔT_{io}.

12.4 R-value calculator and energy savings estimation

Users of this estimator should be familiar with operational caveats to the systems displayed and have a good understanding of COP, EER and SEER (coefficient of performance, energy efficiency ratio and seasonal energy efficiency ratio).

The spreadsheet gives result of energy cost per million BTU, energy usage before and after and estimated savings based on these values. This is just for heat loss through the wall by conduction. It does not include air leaks which are often reduced substantially by adding insulation.

There are a lot of variables for homeowners to consider, so while the energy estimator gives reasonable estimates of potential savings there are numerous additional factors to consider to achieve real savings.

The key element here is the energy savings calculator directly relates what one finds with the IR camera and calculates for R-Value to potential savings for specific insulation retrofit actions taken for the homeowner's specific environment and conditions. As such it is a very useful tool for the building IR thermographer.

12.5 R-value measurement procedure

1 The wall to be measured is an outside wall. Best to measure from inside the home. The procedure is based on this.

2 Wall must be free of pictures, furniture, clocks or other objects that preclude a direct view of the walls surface. If these must be removed, do it 2 to 4 hours prior to measurement. Avoid measuring wall surfaces with conditioned air blowing directly on them. Avoid measuring solar loaded walls. Do them before the sun hits them or wait several hours after the sun is off the wall. Avoid rainy and windy conditions.

3 Inside to outside temperature difference should be at least 18°F (10°C), higher for well-insulated walls.

4 Steady state conditions strongly preferred. You would like the inside to outside temperature difference to be reasonably constant for at least 3 to 4 hours prior to measurement. Look at the plots in figures 3 and 4 to see how the R-Value calculation changes with variations in temperature. For the real world calculation (figure 3 and table 1) there was about a 7°F variation that gave values with a 12% uncertainty. Selecting a time frame with about half the variation, improved the uncertainty significantly. Note, inside to outside delta-T was about a 30°F. You are going to get one number, so you won't have the luxury of the intensive data analysis done here. Use it, though, as a guideline.

5 To get Treflect, crumple a piece of aluminum foil of an area large enough to be resolved by your IR camera. Re-flatten and attach to a piece of paper or thin cardboard. For most IR cameras a standard paper size with half covered with the foil and the other half bare suffices.
6 Support this target 12 to 18 inches from the surface to be measured and allow to come to thermal equilibrium with the room air. This should only take a few minutes. A person could hold this, but the fewer hot bodies in the scene, the better.
7 Take an IR image of the wall target wall surface including your standard target. Continue until all the areas of interest are covered. Be sure your paper/foil standard target is in all the images. Avoid human heat reflection off the foil by viewing at an angle to the IR camera. In fact, for IR cameras with periodic save feature, putting your IR camera on a tripod and using periodic save mode is the preferred approach. Set the period to something like 30 seconds and let the IR camera take 2 or 3 images with no one in the room.
8 Finally, go outside and take one more IR image of the standard target after it has come to thermal equilibrium with the outdoor air temperature.
9 For $T_{reflect}$, set your IR camera emissivity to 1.0 and take an average temperature reading of an area on the foil target for each wall surface measured. (This complies with ASTM 1862-97 and ISO 18434-1 standards). Also, input this value for getting the temperatures of the paper (indoor air) and wall (wall surface).
10 With proper $T_{reflect}$ (aka T_{rat}, $T_{background}$) found in step 10 and proper emissivity; get the temperatures of other areas of interest.
11 From the uncertainty analysis below, the most sensitive variables are the emissivity and the temperature difference between $T_{reflect}$ and T_{wall}. Do these very carefully! The emissivity of paper and cardboard is typically 0.95 for long wave IR cameras. Most wall surfaces also have an emissivity of 0.95, unless they have a special treatment.
12 Use the Excel spreadsheet software developed by the Infrared Training Center to calculate R-Value.

12.6 Uncertainty analysis

Important temperature variables are the temperature differences between inside and outside, inside and wall and reflected apparent temperature and wall. The absolute temperature is also somewhat important. Emissivity value and the characteristic length round out the variables.

The most sensitive variable is the temperature difference between the reflected apparent temperature and the wall temperature.

The emissivity is the next most sensitive variable with the characteristic length, L, and the inside to outside temperature differences being the least sensitive.

For the higher R-Values a higher delta-T is needed to keep the uncertainty at a reasonable level. The 18°F delta-T used in many standards isn't bad for moderate R-Values, but for R-Values higher than R-11, one would prefer a 30 or even 40°F delta-T.

12.7 Summary and conclusions

Measuring R-Value requires close to steady state conditions and following a good procedure to get meaningful results. But steady state conditions may not be the most significant culprit for error contribution. The real world example showed lack of steady state conditions still allowed good results. The procedure of using the same, high quality IR camera for all temperature measurements is an extremely important factor in obtaining these results.

13 Introduction to building thermography

13.1 *Important note*

All camera functions and features that are described in this section may not be supported by your particular camera configuration.

13.2 *Typical field investigations*

13.2.1 Guidelines

As will be noted in subsequent sections there are a number of general guidelines the user should take heed of when carrying out building thermography inspection. This section gives a summary of these guidelines.

13.2.1.1 General guidelines

- The emissivity of the majority of building materials fall between 0.85 and 0.95. Setting the emissivity value in the camera to 0.90 can be regarded as a good starting point.
- An infrared inspection alone should never be used as a decision point for further actions. Always verify suspicions and findings using other methods, such as construction drawings, moisture meters, humidity & temperature datalogging, tracer gas testing etc.
- Change level and span to thermally tune the infrared image and reveal more details. The figure below shows the difference between a thermally untuned and a thermally tuned infrared image.

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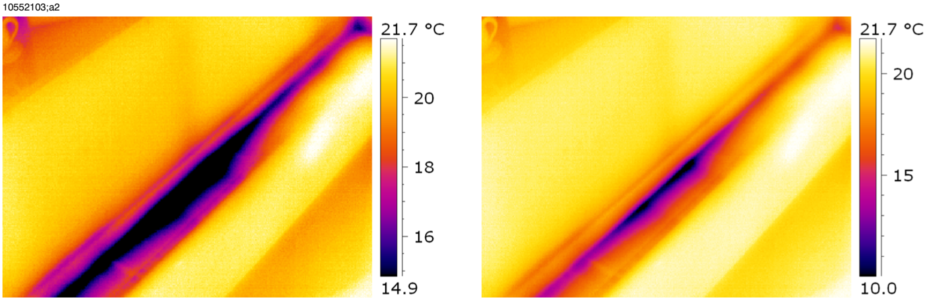


Figure 13.1 LEFT: A thermally untuned infrared image; **RIGHT:** A thermally tuned infrared image, after having changed level and span.

13.2.1.2 Guidelines for moisture detection, mold detection & detection of water damages

- Building defects related to moisture and water damages may only show up when heat has been applied to the surface, e.g. from the sun.
- The presence of water changes the thermal conductivity and the thermal mass of the building material. It may also change the surface temperature of building material due to evaporative cooling. Thermal conductivity is a material's ability to conduct heat, while thermal mass is its ability to store heat.
- Infrared inspection does not directly detect the presence of mold, rather it may be used to find moisture where mold may develop or has already developed. Mold requires temperatures between +4°C to +38°C (+40°F to +100°F), nutrients and moisture to grow. Humidity levels above 50% can provide sufficient moisture to enable mold to grow.

10556003;a1

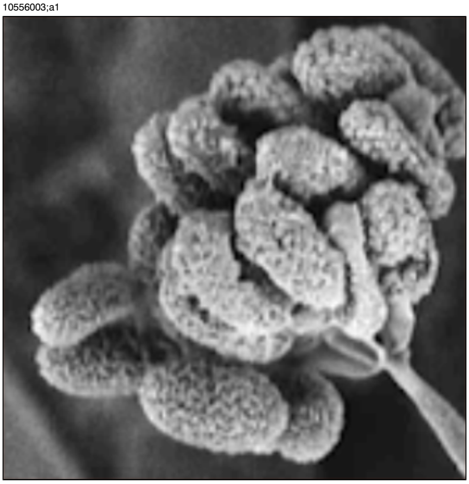


Figure 13.2 Microscopic view of mold spore

13.2.1.3 Guidelines for detection of air infiltration & insulation deficiencies

- For very accurate camera measurements, take measurements of the temperature and enter this value in the camera.
- It is recommended that there is a difference in pressure between the outside and the inside of the building structure. This facilitates the analysis of the infrared images and reveals deficiencies that would not be visible otherwise. Although a negative pressure of between 10 and 50 Pa is recommended, carrying out the inspection at a lower negative pressure may be acceptable. To do this, close all windows, doors and ventilation ducts and then run the kitchen exhaust fan for some time to reach a negative pressure of 5–10 Pa (applies to residential houses only).

- A difference in temperature between the inside and the outside of 10–15°C (18–27°F) is recommended. Inspections can be carried out at a lower temperature difference, but will make the analysis of the infrared images somewhat more difficult.
- Avoid direct sunlight on a part of a building structure—e.g. a façade—that is to be inspected from the inside. The sunlight will heat the façade which will equalize the temperature differences on the inside and mask deficiencies in the building structure. Spring seasons with low nighttime temperatures (±0°C (+32°F)) and high daytime temperatures (+14°C (+57°F)) are especially risky.

13.2.2 About moisture detection

Moisture in a building structure can originate from several different sources, e.g.:

- External leaks, such as floods, leaking fire hydrants etc.
- Internal leaks, such as freshwater piping, waste water piping etc.
- Condensation, which is humidity in the air falling out as liquid water due to condensation on cold surfaces.
- Building moisture, which is any moisture in the building material prior to erecting the building structure.
- Water remaining from firefighting.

As a non-destructive detection method, using an infrared camera has a number of advantages over other methods, and a few disadvantages:

Advantage	Disadvantage
■ The method is quick. ■ The method is a non-intrusive means of investigation. ■ The method does not require relocation of the occupants. ■ The method features an illustrative visual presentation of findings. ■ The method confirms failure points and moisture migration paths.	■ The method only detects surface temperature differentials and can not see through walls. ■ The method can not detect subsurface damage, i.e. mold or structural damage.

13.2.3 Moisture detection (1): Low-slope commercial roofs

13.2.3.1 General information

Low-slope commercial roofing is one of the most common roof types for industrial building, such as warehouses, industrial plants, machinery shops etc. Its major advantages over a pitched roof is the lower cost in material and building. However, due to its design where snow and ice will not fall off by itself—as is the case for the majority of pitched roofs—it must be strongly built to support the accumulated weight of both roof structure and any snow, ice and rain.

Although a basic understanding of the construction of low-slope commercial roofs is desirable when carrying out a roof thermography inspection, expert knowledge is not necessary. There is a large number of different design principles for low-slope commercial roofs—both when it comes to material and design—and it would be impossible for the infrared inspection person to know them all. If additional information about a certain roof is needed, the architect or contractor of the building can usually supply the relevant information.

Common causes of roof failure are outlined in the table below (from SPIE Thermosense Proceedings Vol. 371 (1982), p. 177).

Cause	%
Poor workmanship	47.6
Roof traffic	2.6
Poor design	16.7
Trapped moisture	7.8
Materials	8.0
Age & weathering	8.4

Potential leak locations include the following:

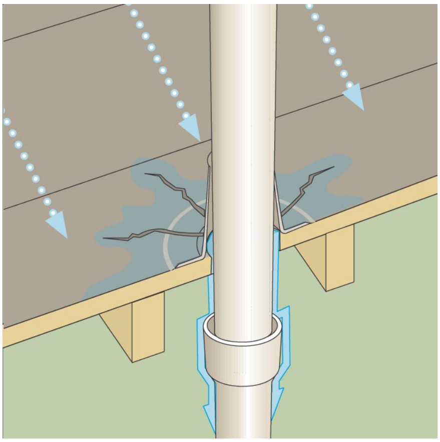
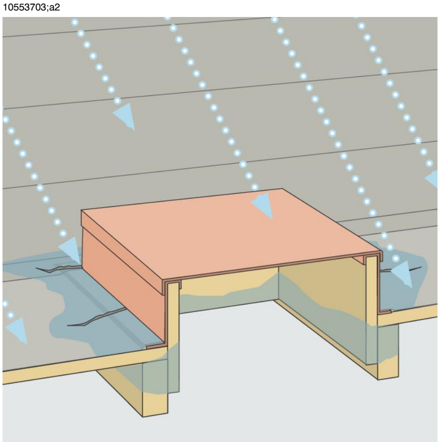
- Flashing
- Drains
- Penetrations
- Seams
- Blisters

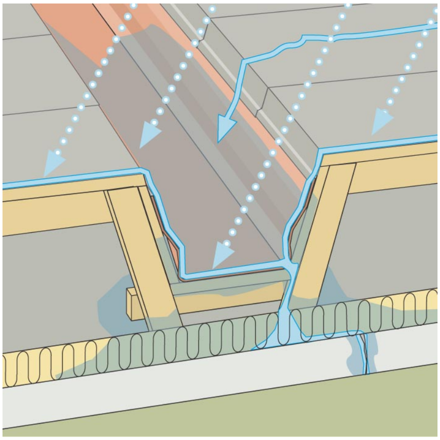
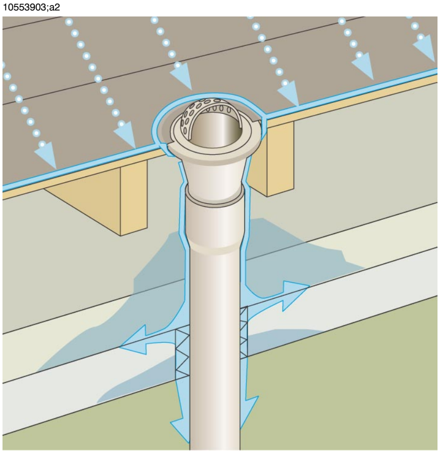
13.2.3.2 Safety precautions

- Recommend a minimum of two people on a roof, preferably three or more.
- Inspect the underside of the roof for structural integrity prior to walking on it.
- Avoid stepping on blisters that are common on built up bitumen and gravel roofs.
- Have a cell phone or radio available in case of emergency.
- Inform local police and plant security prior to doing nighttime roof survey.

13.2.3.3 Commented building structures

This section includes a few typical examples of moisture problems on low-slope commercial roofs.

Structural drawing	Comment
10553603;a2 	Inadequate sealing of roof membrane around conduit and ventilation ducts leading to local leakage around the conduit or duct.
10553703;a2 	Roof membrane inadequately sealed around roof access hatch.

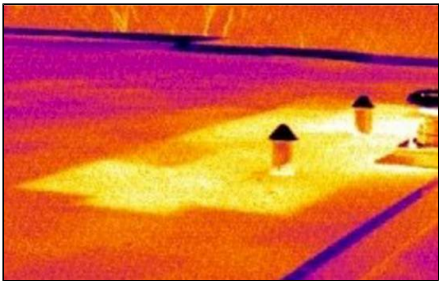
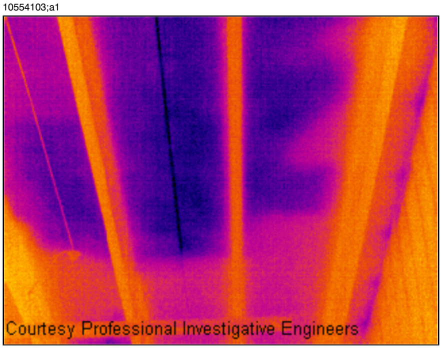
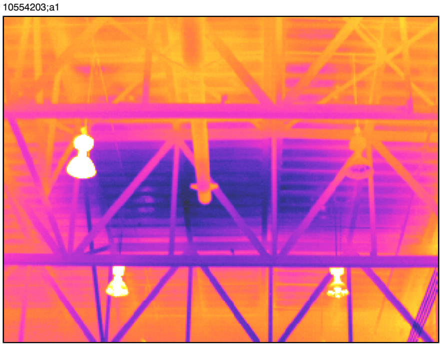
Structural drawing	Comment
10553803;a2 	Drainage channels located too high and with too low an inclination. Some water will remain in the drainage channel after rain, which may lead to local leakage around the channel.
10553903;a2 	Inadequate sealing between roof membrane and roof outlet leading to local leakage around the roof outlet.

13.2.3.4 *Commented infrared images*

How do you find wet insulation below the surface of the roof? When the surface itself is dry, including any gravel or ballast, a sunny day will warm the entire roof. Early in the evening, if the sky is clear, the roof will begin to cool down by radiation. Because of its higher thermal capacity the wet insulation will stay warmer longer than the dry and will be visible in the infrared camera (see photos below). The technique is particularly effective on roofs having absorbent insulation—such as wood fiber, fiberglass, and perlite—where thermal patterns correlate almost perfectly with moisture.

Infrared inspections of roofs with nonabsorbent insulations, common in many single-ply systems, are more difficult to diagnose because patterns are more diffuse.

This section includes a few typical infrared images of moisture problems on low-slope commercial roofs:

Infrared image	**Comment**
10554003;a1 	Moisture detection on a roof, recorded during the evening. Since the building material affected by moisture has a higher thermal mass, its temperature decreases slower than surrounding areas.
10554103;a1 	Water-damaged roofing components and insulation identified from infrared scan from the underside of the built-up roof on a structural concrete tee deck. Affected areas are cooler than the surrounding sound areas, due to conductive and/or thermal capacitive effect.
10554203;a1 	Daytime survey of built-up low-slope commercial roof. Affected areas are cooler than the surrounding dry areas, due to conductive and/or thermal capacitive effect.

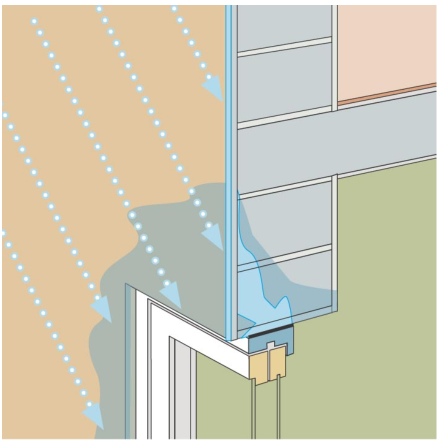
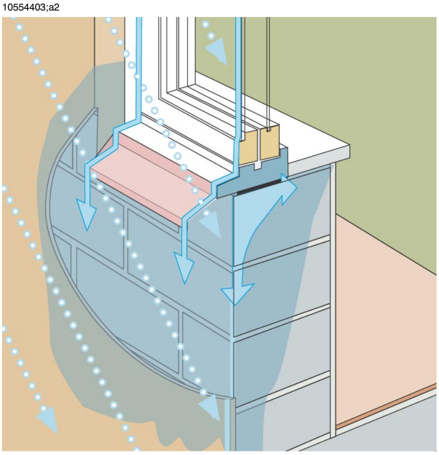
13.2.4 Moisture detection (2): Commercial & residential façades

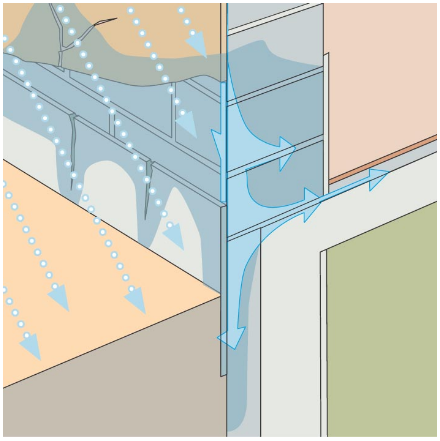
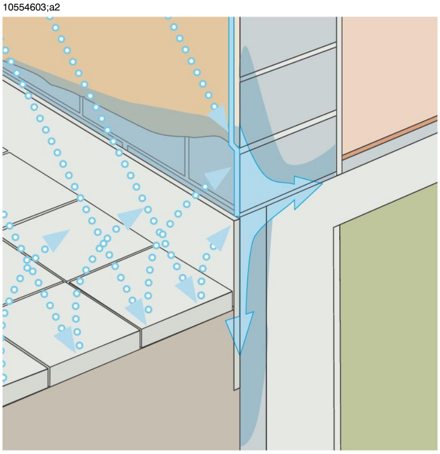
13.2.4.1 General information

Thermography has proven to be invaluable in the assessment of moisture infiltration into commercial and residential façades. Being able to provide a physical illustration of the moisture migration paths is more conclusive than extrapolating moisture meter probe locations and more cost-effective than large intrusive test cuts.

13.2.4.2 Commented building structures

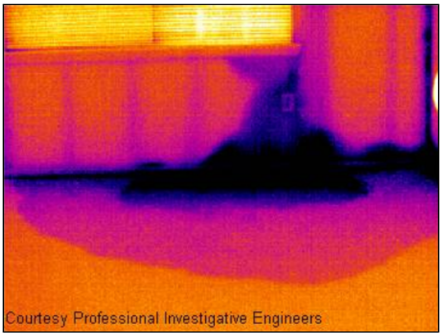
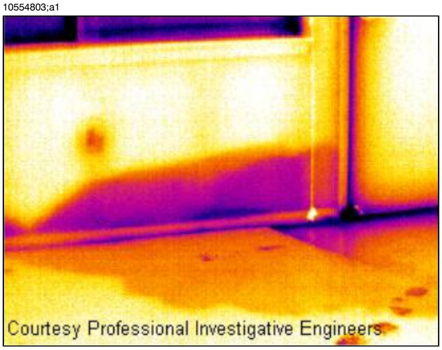
This section includes a few typical examples of moisture problems on commercial and residential façades.

Structural drawing	Comment
10554303;a2 	Pelting rain penetrates the façade due to badly executed bed joints. Moisture builds up in the masonry above the window.
10554403;a2 	Pelting rain hits the window at an angle. Most of the rain runs off the window edge flashing but some finds its way into the masonry where the plaster meets the underside of the flashing.

Structural drawing	Comment
10554503;a2 	Rain hits the façade at an angle and penetrates the plaster through cracks. The water then follows the inside of the plaster and leads to frost erosion.
10554603;a2 	Rain splashes on the façade and penetrates the plaster and masonry by absorption, which eventually leads to frost erosion.

13.2.4.3 Commented infrared images

This section includes a few typical infrared images of moisture problems on commercial & residential façades.

Infrared image	Comment
10554703;a1 	Improperly terminated and sealed stone veneer to window frame and missing flashings has resulted in moisture infiltration into the wall cavity and interior living space.
10554803;a1 	Moisture migration into drywall from capillary drive and interior finish components from inadequate clearance and slope of grade from vinyl siding façade on an apartment complex.

13.2.5 Moisture detection (3): Decks & balconies

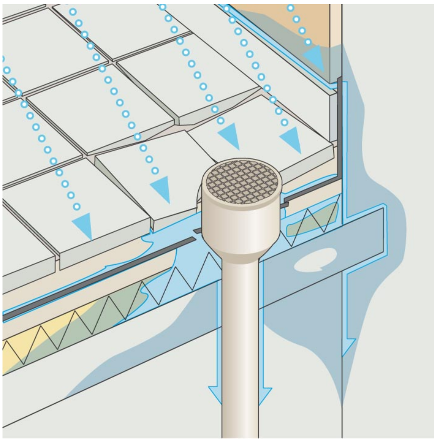
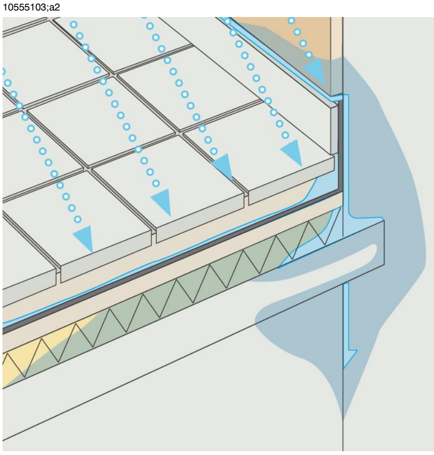
13.2.5.1 General information

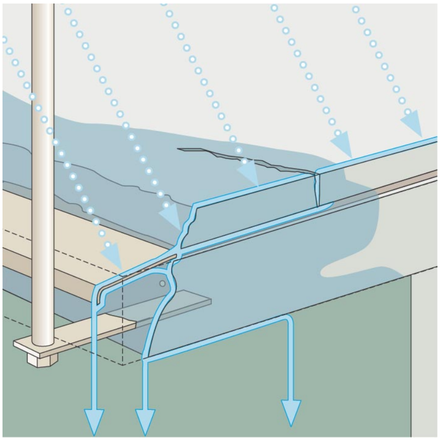
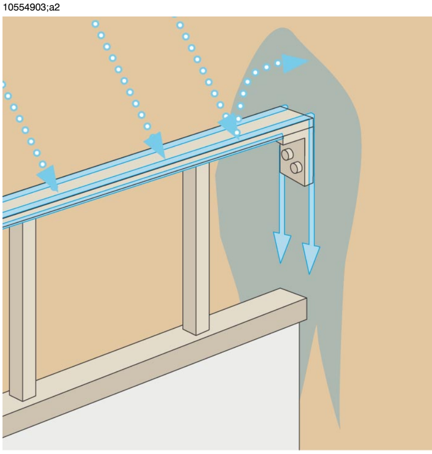
Although there are differences in design, materials and construction, decks—plaza decks, courtyard decks etc—suffer from the same moisture and leaking problems as low-slope commercial roofs. Improper flashing, inadequately sealed membranes, and insufficient drainage may lead to substantial damage in the building structures below.

Balconies, although smaller in size, require the same care in design, choice of material, and workmanship as any other building structure. Since balconies are usually supported on one side only, moisture leading to corrosion of struts and concrete reinforcement can cause problems and lead to hazardous situations.

13.2.5.2 Commented building structures

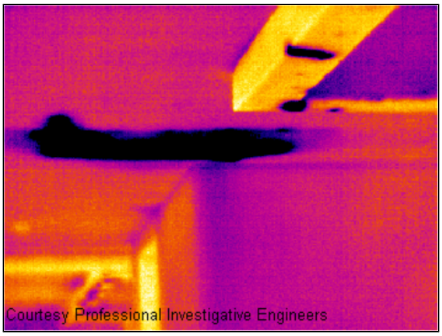
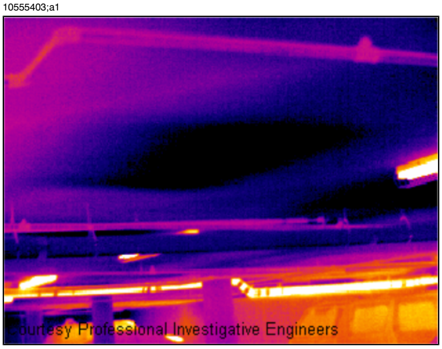
This section includes a few typical examples of moisture problems on decks and balconies.

Structural drawing	Comment
10555203;a2 	Improper sealing of paving and membrane to roof outlet, leading to leakage during rain.
10555103;a2 	No flashing at deck-to-wall connection, leading to rain penetrating the concrete and insulation.

Structural drawing	Comment
10555003;a2 	Water has penetrated the concrete due to inadequately sized drop apron and has led to concrete disintegration and corrosion of reinforcement. SECURITY RISK!
10554903;a2 	Water has penetrated the plaster and underlying masonry at the point where the handrail is fastened to the wall. SECURITY RISK!

13.2.5.3 Commented infrared images

This section includes a few typical infrared images of moisture problems on decks and balconies.

Infrared image	Comment
10555303;a1 	Improper flashing at balcony-to-wall connections and missing perimeter drainage system resulted in moisture intrusion into the wood framing support structure of the exterior walkway balcony of a loft complex.
10555403;a1 	A missing composite drainage plane or medium on a below-grade parking garage plaza deck structure resulted in standing water between the structural concrete deck and the plaza wearing surface.

13.2.6 Moisture detection (4): Plumbing breaks & leaks

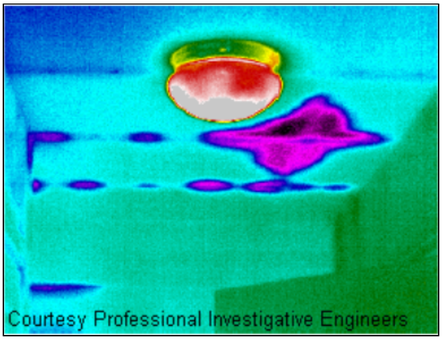
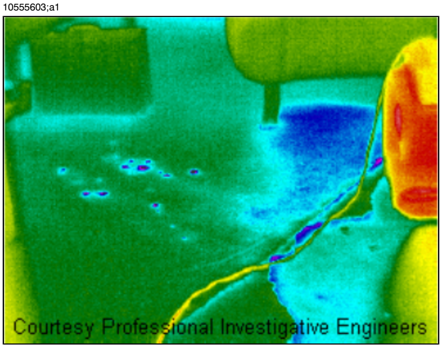
13.2.6.1 General information

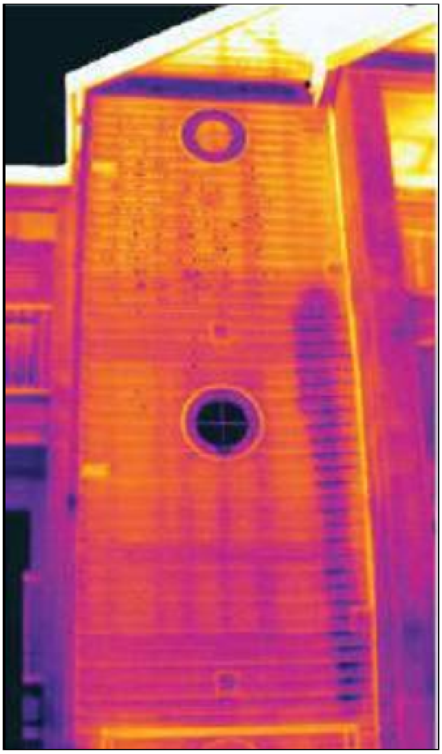
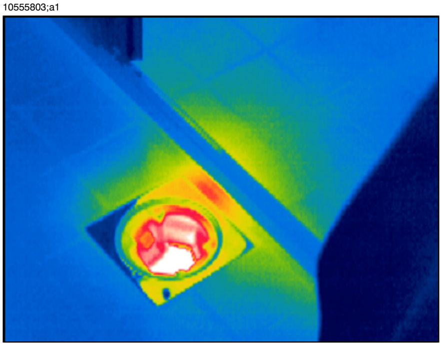
Water from plumbing leaks can often lead to severe damage on a building structure. Small leaks may be difficult to detect, but can—over the years—penetrate structural walls and foundations to a degree where the building structure is beyond repair.

Using building thermography at an early stage when plumbing breaks and leaks are suspected can lead to substantial savings on material and labor.

13.2.6.2 Commented infrared images

This section includes a few typical infrared images of plumbing breaks & leaks.

Infrared image	Comment
10555503;a1 	Moisture migration tracking along steel joist channels inside ceiling of a single family home where a plumbing line had ruptured.
10555603;a1 	Water from plumbing leak was found to have migrated farther than originally anticipated by the contractor during remediation techniques of cutting back carpet and installing dehumidifiers.

Infrared image	Comment
10555703;a1 	The infrared image of this vinyl-sided 3-floor apartment house clearly shows the path of a serious leak from a washing machine on the third floor, which is completely hidden within the wall.
10555803;a1 	Water leak due to improper sealing between floor drain and tiles.

13.2.7 Air infiltration

13.2.7.1 General information

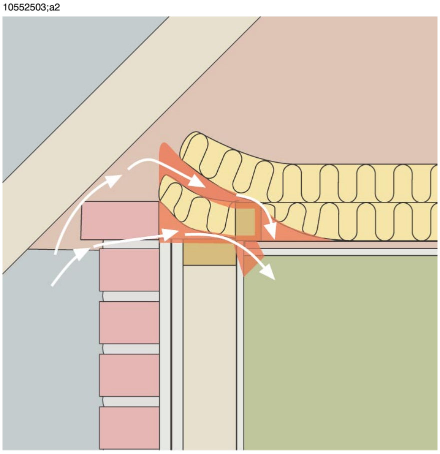
Due to the wind pressure on a building, temperature differences between the inside and the outside of the building, and the fact that most buildings use exhaust air terminal devices to extract used air from the building, a negative pressure of 2–5 Pa can be expected. When this negative pressure leads to cold air entering the building structure due to deficiencies in building insulation and/or building sealing, we have what is called *air infiltration*. Air infiltration can be expected at joints and seams in the building structure.

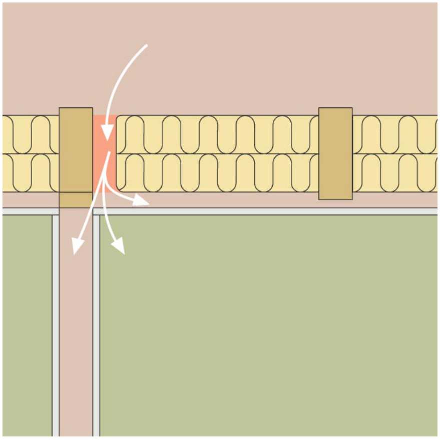
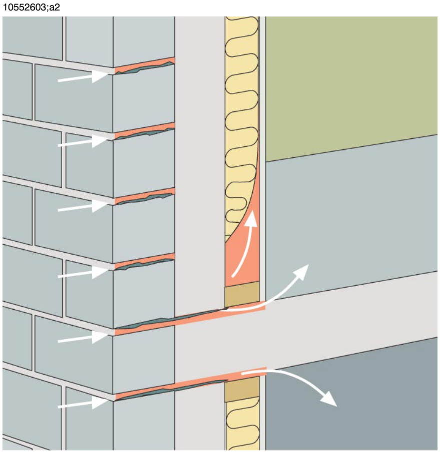
Due to the fact that air infiltration creates an air flow of cool air into e.g. a room, it can lead to substantial deterioration of the indoor climate. Air flows as small as 0.15 m/s (0.49 ft./s) are usually noticed by inhabitants, although these air flows may be difficult to detect using ordinary measurement devices.

On an infrared image air infiltration can be identified by its typical ray pattern, which emanates from the point of exit in the building structure—e.g. from behind a skirting strip. Furthermore, areas of air infiltration typically have a lower detected temperature than areas where there is only an insulation deficiency. This is due to the chill factor of the air flow.

13.2.7.2 Commented building structures

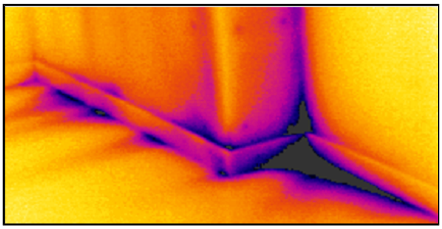
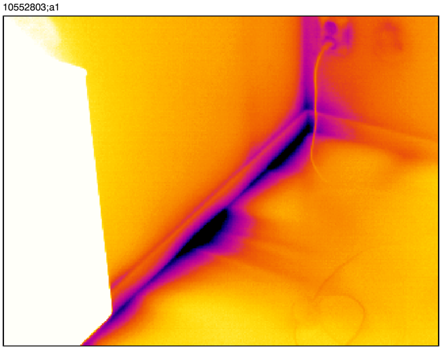
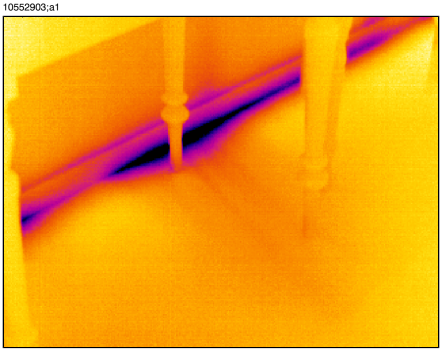
This section includes a few typical examples of details of building structures where air infiltration may occur.

Structural drawing	**Comment**
10552503;a2 	Insulation deficiencies at the eaves of a brickwall house due to improperly installed fiberglass insulation batts. The air infiltration enters the room from behind the cornice.

Structural drawing	Comment
10552303;a2 	Insulation deficiencies in an intermediate flow due to improperly installed fiberglass insulation batts. The air infiltration enters the room from behind the cornice.
10552603;a2 	Air infiltration in a concrete floor-over-crawl-space due to cracks in the brick wall façade. The air infiltration enters the room beneath the skirting strip.

13.2.7.3 Commented infrared images

This section includes a few typical infrared images of details of building structures where air infiltration has occurred.

Infrared image	Comment
10552703;a1 	Air infiltration from behind a skirting strip. Note the typical ray pattern.
10552803;a1 	Air infiltration from behind a skirting strip. Note the typical ray pattern. The white area to the left is a radiator.
10552903;a1 	Air infiltration from behind a skirting strip. Note the typical ray pattern.

13.2.8 Insulation deficiencies

13.2.8.1 General information

Insulation deficiencies do not necessarily lead to air infiltration. If fiberglass insulation batts are improperly installed air pockets will form in the building structure. Since these air pockets have a different thermal conductivity than areas where the insulation batts are properly installed, the air pockets can be detected during a building thermography inspection.

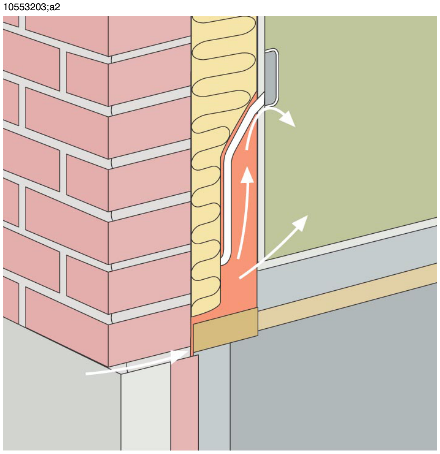
As a rule of thumb, areas with insulation deficiencies typically have higher temperatures than where there is only an air infiltration.

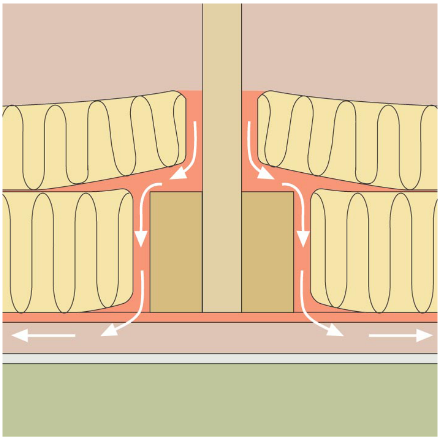
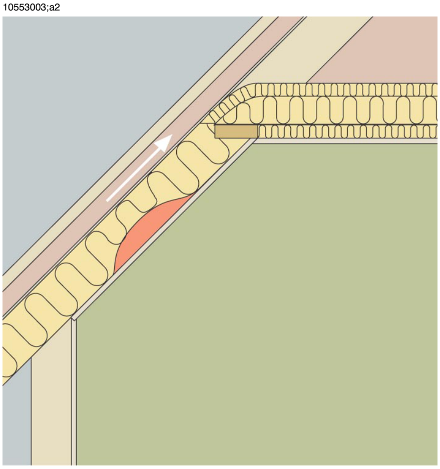
When carrying out building thermography inspections aimed at detecting insulation deficiencies, be aware of the following parts in a building structure, which may look like insulation deficiencies on the infrared image:

- Wooden joists, studs, rafter, beams
- Steel girders and steel beams
- Water piping inside walls, ceilings, floors
- Electrical installations inside walls, ceilings, floors—such as trunking, piping etc.
- Concrete columns inside timber framed walls
- Ventilation ducts & air ducts

13.2.8.2 Commented building structures

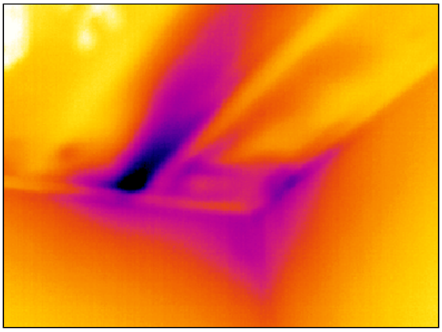
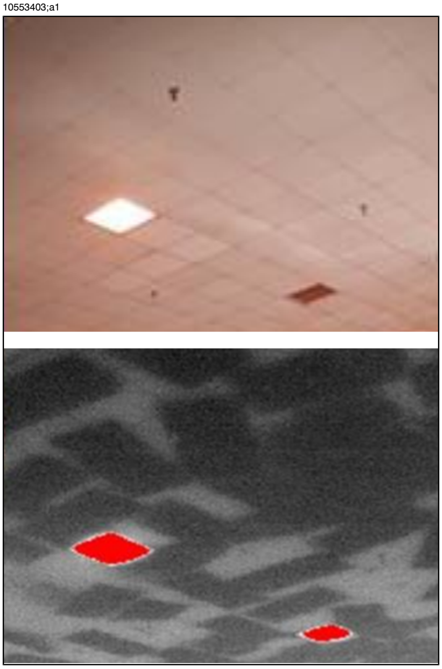
This section includes a few typical examples of details of building structures with insulation deficiencies:

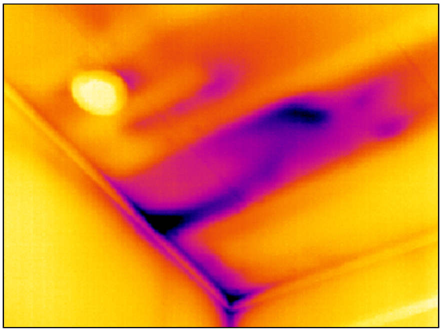
Structural drawing	Comment
10553203;a2 	Insulation deficiencies (and air infiltration) due to improper installation of insulation batts around an electrical mains supply. This kind of insulation deficiency will show up as dark areas on an infrared image.

Structural drawing	Comment
10553103;a2 	Insulation deficiencies due to improper installation of insulation batts around an attic floor beam. Cool air infiltrates the structure and cools down the inside of the ceiling. This kind of insulation deficiency will show up as dark areas on an infrared image.
10553003;a2 	Insulation deficiencies due to improper installation of insulation batts creating an air pocket on the outside of an inclined ceiling. This kind of insulation deficiency will show up as dark areas on an infrared image.

13.2.8.3 Commented infrared images

This section includes a few typical infrared images of insulation deficiencies.

Infrared image	Comment
10553303;a1 	Insulation deficiencies in an intermediate floor structure. The deficiency may be due to either missing insulation batts or improperly installed insulations batts (air pockets).
10553403;a1 	Improperly installed fiberglass batts in a suspended ceiling.

Infrared image	Comment
10553503;a1 	Insulation deficiencies in an intermediate floor structure. The deficiency may be due to either missing insulation batts or improperly installed insulations batts (air pockets).

13.3 Theory of building science

13.3.1 General information

The demand for energy-efficient constructions has increased significantly in recent times. Developments in the field of energy, together with the demand for pleasant indoor environments, have resulted in ever-greater significance having to be attached to both the function of a building's thermal insulation and airtightness and the efficiency of its heating and ventilation systems.

Defective insulation and tightness in highly insulated and airtight structures can have a great impact on energy losses. Defects in a building's thermal insulation and airtightness do not merely entail risk of excessive heating and maintenance costs, they also create the conditions for a poor indoor climate.

A building's degree of insulation is often stated in the form of a thermal resistance or a coefficient of thermal transmittance (U value) for the various parts of the building. However, the stated thermal resistance values rarely provide a measure of the actual energy losses in a building. Air leakage from joints and connections that are not airtight and insufficiently filled with insulation often gives rise to considerable deviations from the designed and expected values.

Verification that individual materials and building elements have the promised properties is provided by means of laboratory tests. Completed buildings have to be checked and inspected in order to ensure that their intended insulation and airtightness functions are actually achieved.

In its structural engineering application, thermography is used to study temperature variations over the surfaces of a structure. Variations in the structure's thermal resistance can, under certain conditions, produce temperature variations on its surfaces. Leakage of cold (or warm) air through the structure also affects the variation in surface temperature. This means that insulation defects, thermal bridges and air leaks in a building's enclosing structural components can be located and surveyed.

Thermography itself does not directly show the structure's thermal resistance or airtightness. Where quantification of thermal resistance or airtightness is required, additional measurements have also to be taken. Thermographic analysis of buildings relies on certain prerequisites in terms of temperature and pressure conditions across the structure.

Details, shapes and contrasts in the thermal image can vary quite clearly with changes in any of these parameters. The in-depth analysis and interpretation of thermal images therefore requires thorough knowledge of such aspects as material and structural properties, the effects of climate and the latest measuring techniques. For assessing

the results of measurements, there are special requirements in terms of the skills and experience of those taking the measurements, e.g. by means of authorization by a national or regional standardization body.

13.3.2 The effects of testing and checking

It can be difficult to anticipate how well the thermal insulation and airtightness of a completed building will work. There are certain factors involved in assembling the various components and building elements that can have a considerable impact on the final result. The effects of transport, handling and storage at the site and the way the work is done cannot be calculated in advance. To ensure that the intended function is actually achieved, verification by testing and checking the completed building is required.

Modern insulation technology has reduced the theoretical heat requirement. This does mean, however, that defects that are relatively minor, but at important locations, e.g. leaking joints or incorrectly installed insulation, can have considerable consequences in terms both of heat and comfort. Verification tests, e.g. by means of thermography, have proved their value, from the point of view both of the designer and the contractor and of the developer, the property manager and the user.

- For the designer, the important thing is to find out about the function of various types of structures, so that they can be designed to take into account both working methods and functional requirements. The designer must also know how different materials and combinations of materials function in practice. Effective testing and checking, as well as experiential feedback, can be used to achieve the required development in this area.
- The contractor is keen on more testing and inspection in order to ensure that the structures keep to an expected function that corresponds to established requirements in the regulations issued by authorities and in contractual documents. The contractor wants to know at an early stage of construction about any changes that may be necessary so that systematic defects can be prevented. During construction, a check should therefore be carried out on the first apartments completed in a mass production project. Similar checking then follows as production continues. In this way systematic defects can be prevented and unnecessary costs and future problems can be avoided. This check is of benefit both to manufacturers and to users.
- For the developer and the property manager it is essential that buildings are checked with reference to heat economy, maintenance (damage from moisture or moisture infiltration) and comfort for the occupants (e.g. cooled surfaces and air movements in occupied zones).

- For the user the important thing is that the finished product fulfills the promised requirements in terms of the building's thermal insulation and airtightness. For the individual, buying a house involves a considerable financial commitment, and the purchaser therefore wants to know that any defects in the construction will not involve serious financial consequences or hygiene problems.

The effects of testing and checking a building's insulation and airtightness are partly physiological and partly financial.

The physiological experience of an indoor climatic environment is very subjective, varying according to the particular human body's heat balance and the way the individual experiences temperature. The experience of climate depends on both the indoor air temperature and that of the surrounding surfaces. The speed of movement and moisture content of indoor air are also of some significance. Physiologically, a draft produces the sensation of local cooling of the body's surface caused by

- excessive air movements in the occupied zone with normal air temperature;
- normal air movements in the occupied zone but a room temperature that is too low;
- substantial radiated heat exchange with a cold surface.

It is difficult to assess the quantitative effects of testing and checking a building's thermal insulation.

Investigations have shown that defects found in the thermal insulation and airtightness of buildings cause heat losses that are about 20–30% more than was expected. Monitoring energy consumption before and after remedial measures in relatively large complexes of small houses and in multi-dwelling blocks has also demonstrated this. The figures quoted are probably not representative of buildings in general, since the investigation data cannot be said to be significant for the entire building stock. A cautious assessment however would be that effectively testing and checking a building's thermal insulation and airtightness can result in a reduction in energy consumption of about 10%.

Research has also shown that increased energy consumption associated with defects is often caused by occupants increasing the indoor temperature by one or a few degrees above normal to compensate for the effect of annoying thermal radiation towards cooled surfaces or a sensation of disturbing air movements in a room.

13.3.3 Sources of disruption in thermography

During a thermographic survey, the risk of confusing temperature variations caused by insulation defects with those associated with the natural variation in U values along warm surfaces of a structure is considered slight under normal conditions.

The temperature changes associated with variations in the U value are generally gradual and symmetrically distributed across the surface. Variations of this kind do of course occur at the angles formed by roofs and floors and at the corners of walls.

Temperature changes associated with air leaks or insulation defects are in most cases more evident with characteristically shaped sharp contours. The temperature pattern is usually asymmetrical.

During thermography and when interpreting an infrared image, comparison infrared images can provide valuable information for assessment.

The sources of disruption in thermography that occur most commonly in practice are

- the effect of the sun on the surface being thermographed (sunlight shining in through a window);
- hot radiators with pipes;
- lights directed at, or placed near, the surface being measured;
- air flows (e.g. from air intakes) directed at the surface;
- the effect of moisture deposits on the surface.

Surfaces on which the sun is shining should not be subjected to thermography. If there is a risk of an effect by sunlight, windows should be covered up (closing Venetian blinds). However, be aware that there are building defects or problems (typically moisture problems) that only show up when heat has been applied to the surface, e.g. from the sun.

For more information about moisture detection, see section 13.2.2 – About moisture detection on page 53.

A hot radiator appears as a bright light surface in an infrared image. The surface temperature of a wall next to a radiator is raised, which may conceal any defects present.

For maximum prevention of disruptive effects from hot radiators, these may be shut off a short while before the measurement is taken. However, depending on the construction of the building (low or high mass), these may need to be shut off several hours before a thermographic survey. The room air temperature must not fall so much as to affect the surface temperature distribution on the structure's surfaces. There is little timelag with electric radiators, so they cool down relatively quickly once they have been switched off (20–30 minutes).

Lights placed against walls should be switched off when the infrared image is taken.

During a thermographic survey there should not be any disruptive air flows (e.g. open windows, open valves, fans directed at the surface being measured) that could affect the surfaces being thermographed.

Any wet surfaces, e.g. as a result of surface condensation, have a definite effect on heat transfer at the surface and the surface temperature. Where there is moisture on a surface, there is usually some evaporation which draws off heat, thus lowering the temperature of the surface by several degrees. There is risk of surface condensation at major thermal bridges and insulation defects.

Significant disruptions of the kind described here can normally be detected and eliminated before measuring.

If during thermography it is not possible to shield surfaces being measured from disruptive factors, these must be taken into account when interpreting and evaluating the results. The conditions in which the thermography was carried out should be recorded in detail when each measurement is taken.

13.3.4 Surface temperature and air leaks

Defects in building airtightness due to small gaps in the structure can be detected by measuring the surface temperature. If there is a negative pressure in the building under investigation, air flows into the space through leaks in the building. Cold air flowing in through small gaps in a wall usually lowers the temperature in adjacent areas of the wall. The result is that a cooled surface area with a characteristic shape develops on the inside surface of the wall. Thermography can be used to detect cooled surface areas. Air movements at the wall surface can be measured using an air velocity indicator. If there is a positive pressure inside the building being investigated, warm room air will leak out through gaps in the wall, resulting in locally warm surface areas around the locations of the leaks.

The amount of leakage depends partly on gaps and partly on the differential pressure across the structure.

13.3.4.1 Pressure conditions in a building

The most important causes of differential pressure across a structural element in a building are

- wind conditions around the building;
- the effects of the ventilation system;
- temperature differences between air inside and outside (thermal differential pressure).

The actual pressure conditions inside a building are usually caused by a combination of these factors.

The resultant pressure gradient across the various structural elements can be illustrated by the figure on page 79. The irregular effects of wind on a building means that in practice the pressure conditions may be relatively variable and complicated.

In a steady wind flow, Bernoulli's Law applies:

$$\frac{\rho v^2}{2} + p = \text{constant}$$

where:

ρ	Air density in kg/m³
v	Wind velocity in m/s
p	Static pressure in Pa

and where:

$$\frac{\rho v^2}{2}$$

denotes the dynamic pressure and p the static pressure. The total of these pressures gives the total pressure.

Wind load against a surface makes the dynamic pressure become a static pressure against the surface. The magnitude of this static pressure is determined by, amongst other things, the shape of the surface and its angle to the wind direction.

The portion of the dynamic pressure that becomes a static pressure on the surface (p_{stat}) is determined by what is known as a stress concentration factor:

$$C = \frac{p_{stat}}{\frac{\rho v^2}{2}}$$

If ρ is 1.23 kg/m³ (density of air at +15°C (+59°F)), this gives the following local pressures in the wind flow:

$$p_{stat} = C \times \frac{\rho v^2}{2} = C \times \frac{v^2}{1.63} \text{ Pa}$$

10551803;a1

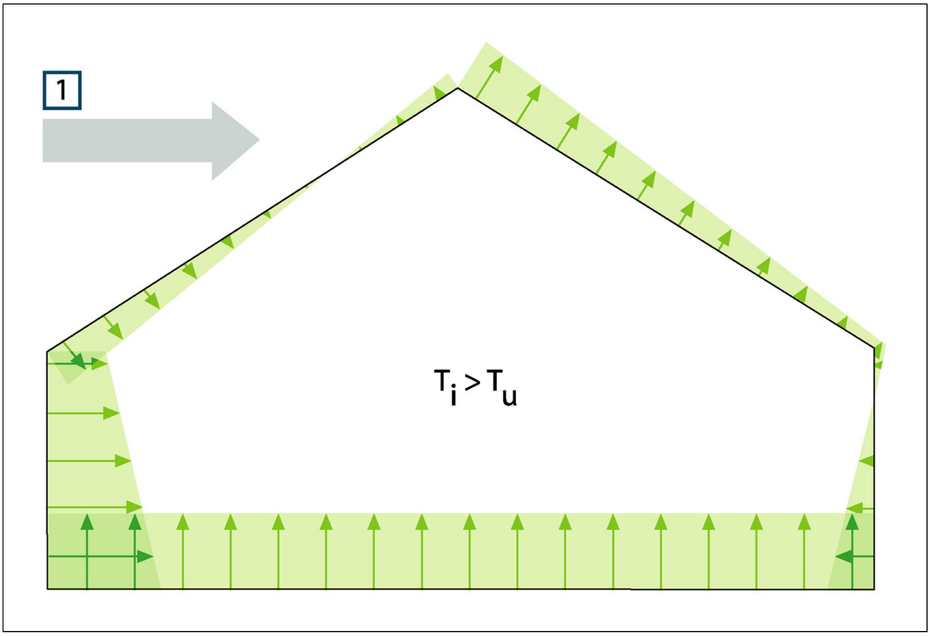


Figure 13.3 Distribution of resultant pressures on a building's enclosing surfaces depending on wind effects, ventilation and internal/external temperature difference. **1**: Wind direction; T_u: Thermodynamic air temperature outdoors in K; T_i: Thermodynamic air temperature indoors in K.

If the whole of the dynamic pressure becomes static pressure, then C = 1. Examples of stress concentration factor distributions for a building with various wind directions are shown in the figure on page 80.

The wind therefore causes an internal negative pressure on the windward side and an internal positive pressure on the leeward side. The air pressure indoors depends on the wind conditions, leaks in the building and how these are distributed in relation to the wind direction. If the leaks in the building are evenly distributed, the internal pressure may vary by ±0.2 p_{stat}. If most of the leaks are on the windward side, the internal pressure increases somewhat. In the opposite case, with most of the leaks on the leeward side, the internal pressure falls.

10551903;a1

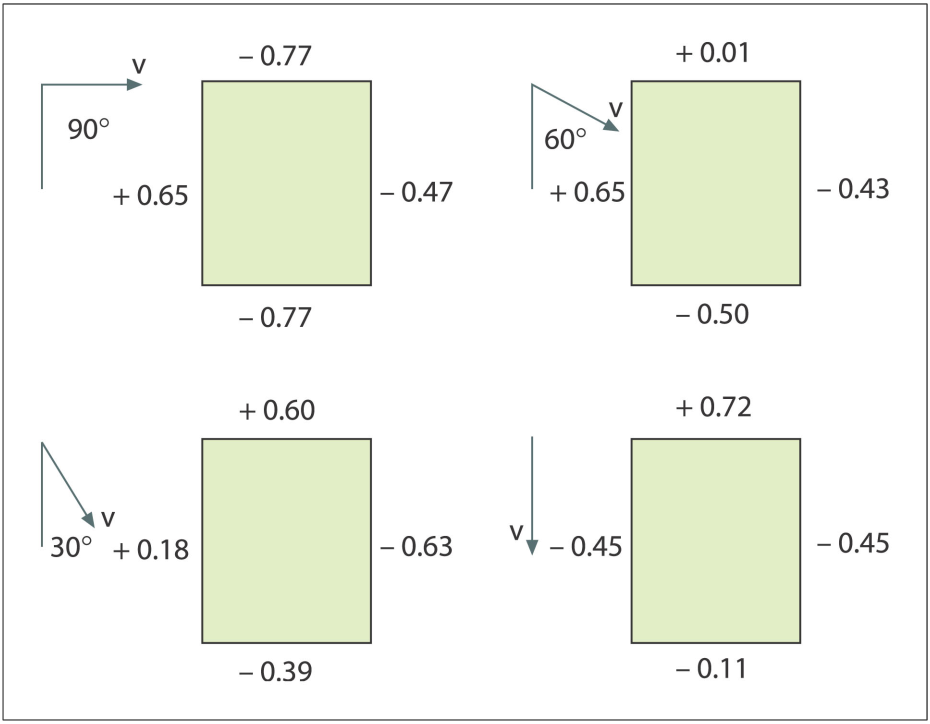


Figure 13.4 Stress concentration factor (C) distributions for various wind directions and wind velocities (v) relative to a building.

Wind conditions can vary substantially over time and between relatively closely situated locations. In thermography, such variations can have a clear effect on the measurement results.

It has been demonstrated experimentally that the differential pressure on a façade exposed to an average wind force of about 5 m/s (16.3 ft/s) will be about 10 Pa.

Mechanical ventilation results in a constant internal negative or positive pressure (depending on the direction of the ventilation). Research has showed that the negative pressure caused by mechanical extraction (kitchen fans) in small houses is usually between 5 and 10 Pa. Where there is mechanical extraction of ventilation air, e.g. in multi-dwelling blocks, the negative pressure is somewhat greater, 10–50 Pa. Where there is so-called balanced ventilation (mechanically controlled supply and extract air), this is normally adjusted to produce a slight negative pressure inside (3–5 Pa).

The differential pressure caused by temperature differences, the so-called chimney effect (airtightness differences of air at different temperatures) means that there is a negative pressure in the building's lower part and a positive pressure in the upper

part. At a certain height there is a neutral zone where the pressures on the inside and outside are the same, see the figure on page 82. This differential pressure may be described by the relationship:

$$\Delta p = g \times \rho_u \times h \left(1 - \frac{T_u}{T_i} \right) \ \mathrm{Pa}$$

Δp	Air pressure differential within the structure in Pa
g	9.81 m/s^2
ρ_u	Air density in kg/m^3
T_u	Thermodynamic air temperature outdoors in K
T_i	Thermodynamic air temperature indoors in K
h	Distance from the neutral zone in meters

If ρ_u = 1.29 kg/m^3 (density of air at a temperature of 273 K and ≈100 kPa), this produces:

$$\Delta p \approx 13 \times h \left(1 - \frac{T_u}{T_i} \right)$$

With a difference of +25°C (+77°F) between the ambient internal and external temperatures, the result is a differential pressure difference within the structure of about 1 Pa/m difference in height (= 3.28 Pa/ft.).

10552003;a1

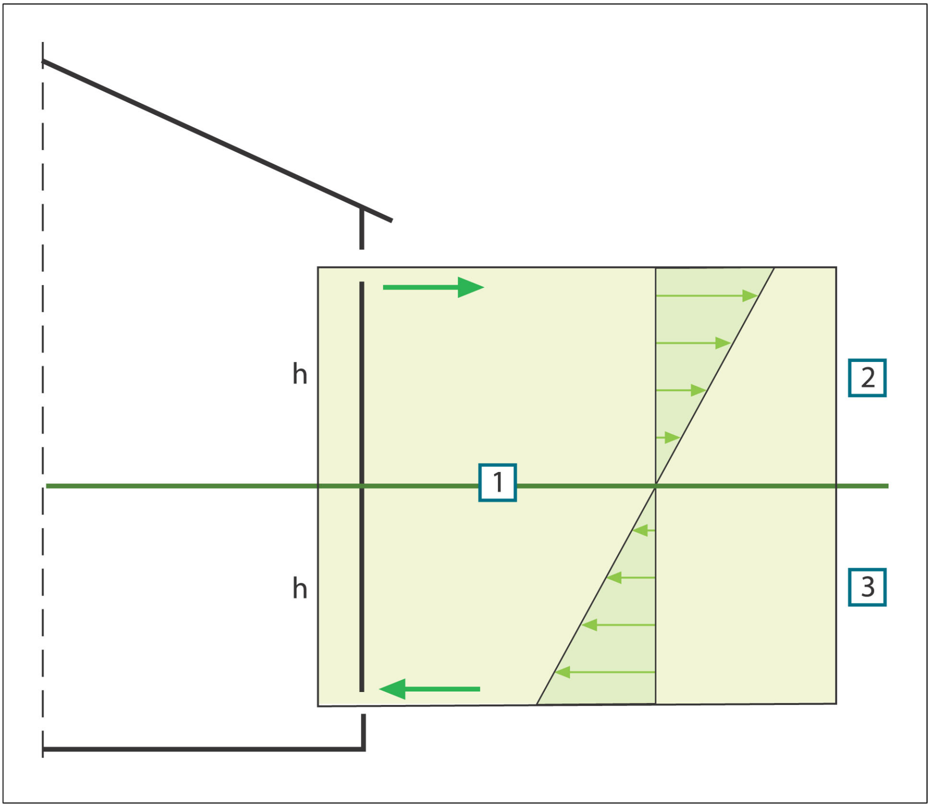


Figure 13.5 Distribution of pressures on a building with two openings and where the external temperature is lower than the internal temperature. **1**: Neutral zone; **2**: Positive pressure; **3**: Negative pressure; **h**: Distance from the neutral zone in meters.

The position of the neutral zone may vary, depending on any leaks in the building. If the leaks are evenly distributed vertically, this zone will be about halfway up the building. If more of the leaks are in the lower part of the building, the neutral zone will move downwards. If more of the leaks are in the upper part, it will move upwards. Where a chimney opens above the roof, this has a considerable effect on the position of the neutral zone, and the result may be a negative pressure throughout the building. This situation most commonly occurs in small buildings.

In a larger building, such as a tall industrial building, with leaks at doors and any windows in the lower part of the building, the neutral zone is about one-third of the way up the building.

13.3.5 Measuring conditions & measuring season

The foregoing may be summarized as follows as to the requirements with regard to measuring conditions when carrying out thermographic imaging of buildings.

Thermographic imaging is done in such a way that the disruptive influence from external climatic factors is as slight as possible. The imaging process is therefore carried out indoors, i.e. where a building is heated, the structure's warm surfaces are examined.

Outdoor thermography is only used to obtain reference measurements of larger façade surfaces. In certain cases, e.g. where the thermal insulation is very bad or where there is an internal positive pressure, outdoor measurements may be useful. Even when investigating the effects of installations located within the building's climatic envelope, there may be justification for thermographic imaging from outside the building.

The following conditions are recommended:

- The air temperature difference within the relevant part of the building must be at least +10°C (+18°F) for a number of hours before thermographic imaging and for as long as the procedure takes. For the same period, the ambient temperature difference must not vary by more than ±30% of the difference when the thermographic imaging starts. During the thermographic imaging, the indoor ambient temperature should not change by more than ±2°C (±3.6°F).
- For a number of hours prior before thermographic imaging and as long as it continues, no influencing sunlight may fall upon the relevant part of the building.
- Negative pressure within the structure ≈ 10–50 Pa.
- When conducting thermographic imaging in order to locate only air leaks in the building's enclosing sections, the requirements in terms of measuring conditions may be lower. A difference of 5°C (9°F) between the inside and outside ambient temperatures ought to be sufficient for detecting such defects. To be able to detect air leaks, certain requirements must however be made with regard to the differential pressure; about 10 Pa should be sufficient.

13.3.6 Interpretation of infrared images

The main purpose of thermography is to locate faults and defects in thermal insulation in exterior walls and floor structures and to determine their nature and extent. The measuring task can also be formulated in such a way that the aim of the thermography is to confirm whether or not the wall examined has the promised insulation and airtightness characteristics. The 'promised thermal insulation characteristics' for the wall according to the design can be converted into an expected surface temperature distribution for the surface under investigation if the measuring conditions at the time when the measurements are taken are known.

In practice the method involves the following:

Laboratory or field tests are used to produce an expected temperature distribution in the form of typical or comparative infrared images for common wall structures, comprising both defect-free structures and structures with in-built defects.

Examples of typical infrared images are shown in section 13.2 – Typical field investigations on page 51.

If infrared images of structural sections taken during field measurements are intended for use as comparison infrared images, then the structure's composition, the way it was built, and the measurement conditions at the time the infrared image was taken must be known in detail and documented.

In order, during thermography, to be able to comment on the causes of deviations from the expected results, the physical, metrological and structural engineering prerequisites must be known.

The interpretation of infrared images taken during field measurements may be described in brief as follows:

A comparison infrared image for a defect-free structure is selected on the basis of the wall structure under investigation and the conditions under which the field measurement was taken. An infrared image of the building element under investigation is then compared with the selected infrared image. Any deviation that cannot be explained by the design of the structure or the measurement conditions is noted as a suspected insulation defect. The nature and extent of the defect is normally determined using comparison infrared images showing various defects.

If no suitable comparison infrared image is available, evaluation and assessment are done on the basis of experience. This requires more precise reasoning during the analysis.

When assessing an infrared image, the following should be looked at:

- Uniformity of brightness in infrared images of surface areas where there are no thermal bridges
- Regularity and occurrence of cooled surface areas, e.g. at studding and corners
- Contours and characteristic shapes in the cooled surface area
- Measured temperature differences between the structure's normal surface temperature and the selected cooled surface area
- Continuity and uniformity of the isotherm curve on the surface of the structure. In the camera software the isotherm function is called **Isotherm** or **Color alarm**, depending on camera model.

Deviations and irregularities in the appearance of the infrared image often indicate insulation defects. There may obviously be considerable variations in the appearance of infrared images of structures with insulation defects. Certain types of insulation defects have a characteristic shape on the infrared image.

Section 13.2 – Typical field investigations on page 51 shows examples of interpretations of infrared images.

When taking infrared images of the same building, the infrared images from different areas should be taken with the same settings on the infrared camera, as this makes comparison of the various surface areas easier.

13.3.7 Humidity & dew point

13.3.7.1 Relative & absolute humidity

Humidity can be expressed in two different ways—either as *relative humidity* or as *absolute humidity*. Relative humidity is expressed in percent of how much water a certain volume of air can hold at a certain temperature, while absolute humidity is expressed in percent water by weight of material. The latter way to express humidity is common when measuring humidity in wood and other building materials.

The higher the temperature of air, the larger the amount of water this certain volume of air can hold. The following table specifies the maximum amounts of water in air at different temperatures.

Figure 13.6 A: Temperature in degrees Celsius; **B:** Maximum amount of water expressed in g/m^3 (at sea level)

A	B	A	B	A	B	A	B
30.0	30.44	20.0	17.33	10.0	9.42	0.0	4.86
29.0	28.83	19.0	16.34	9.0	8.84	-1.0	4.49
28.0	27.29	18.0	15.40	8.0	8.29	-2.0	4.15
27.0	25.83	17.0	14.51	7.0	7.77	-3.0	3.83
26.0	24.43	16.0	13.66	6.0	7.28	-4.0	3.53
25.0	23.10	15.0	12.86	5.0	6.81	-5.0	3.26
24.0	21.83	14.0	12.09	4.0	6.38	-6.0	3.00
23.0	20.62	13.0	11.37	3.0	5.96	-7.0	2.76
22.0	19.47	12.0	10.69	2.0	5.57	-8.0	2.54
21.0	18.38	11.0	10.04	1.0	5.21	-9.0	2.34

Figure 13.7 **A:** Temperature in degrees Fahrenheit; **B:** Maximum amount of water in gr/ft^3 (at sea level)

A	**B**	**A**	**B**	**A**	**B**	**A**	**B**
86.0	13.30	68.0	7.58	50.0	4.12	32.0	2.12
84.2	12.60	66.2	7.14	48.2	3.86	30.2	1.96
82.4	11.93	64.4	6.73	46.4	3.62	28.4	1.81
80.6	11.29	62.6	6.34	44.6	3.40	26.6	1.67
78.8	10.68	60.8	5.97	42.8	3.18	24.8	1.54
77.0	10.10	59.0	5.62	41.0	2.98	23.0.	1.42
75.2	9.54	57.2	5.29	39.2	2.79	21.2	1.31
73.4	9.01	55.4	4.97	37.4	2.61	19.4	1.21
71.6	8.51	53.6	4.67	35.6	2.44	17.6	1.11
69.8	8.03	51.8	4.39	33.8	2.28	15.8	1.02

Example:

The relative humidity of a certain volume of air at a temperature of +30°C (+86°F) is 40 % RH. Amount of water in 1 m^3 (35.31 ft^3) of air at +30°C = 30.44 × Rel Humidity = 30.44 × 0.40 = 12.18 g (187.96 gr).

13.3.7.2 Definition of dew point

Dew point is the temperature at which the humidity in a certain volume of air will condense as liquid water.

Example:

The relative humidity of a certain volume of air at a temperature of +30°C (+86°F) is 40 % RH. Amount of water in 1 m^3 (35.31 ft^3) of air at +30°C = 30.44 × Rel Humidity = 30.44 × 0.40 = 12.18 g (187.96 gr). In the table above, look up the temperature for which the amount of water in air is closest to 12.18 g. This would be +14.0°C (+57.2°F), which is the approximate dew point.

13.3.8 Excerpt from Technical Note ‘Assessing thermal bridging and insulation continuity’ (UK example)

13.3.8.1 Credits

This Technical Note was produced by a working group including expert thermographers, and research consultants. Additional consultation with other persons and organisations results in this document being widely accepted by all sides of industries.

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13.3.8.2 Introduction

Over the last few years the equipment, applications, software, and understanding connected with thermography have all developed at an astonishing rate. As the technology has gradually become integrated into mainstream practises, a corresponding demand for application guides, standards and thermography training has arisen.

The UKTA is publishing this technical note in order to establish a consistent approach to quantifying the results for a 'Continuity of Thermal Insulation' examination. It is intended that specifiers should refer to this document as a guide to satisfying the requirement in the Building Regulations, therefore enabling the qualified thermographer to issue a pass or fail report.

13.3.8.3 Background information

Thermography can detect surface temperature variations as small as 0.1 K and graphic images can be produced that visibly illustrate the distribution of temperature on building surfaces.

Variations in the thermal properties of building structures, such as poorly fitted or missing sections of insulation, cause variations in surface temperature on both sides of the structure. They are therefore visible to the thermographer. However, many other factors such as local heat sources, reflections and air leakage can also cause surface temperature variations.

The professional judgement of the thermographer is usually required to differentiate between real faults and other sources of temperature variation. Increasingly, thermographers are asked to justify their assessment of building structures and, in the absence of adequate guidance, it can be difficult to set definite levels for acceptable or unacceptable variation in temperature.

The current Standard for thermal iamging of building fabric in the UK is BS EN 13187:1999 (BS EN 13187:1999, Thermal Performance of Buildings—Qualitative detection of thermal properties in building envelopes—Infrared method (ISO 6781:1983 modified). However, this leaves interpretation of the thermal image to the professional expertise of of the thermographer and provides little guidance on the demarcation between acceptable and unacceptable variations. Guidance on the appearance of a

range of thermal anomalies can be found in BINDT Guides to thermal imaging (Infrared Thermography Handbook; Volume 1, Principles and Practise, Norman Walker, ISBN 0903132338, Volume 2, Applications, A. N. Nowicki, ISBN 090313232X, BINDT, 2005).

13.3.8.3.1 Requirements

A thermographic survey to demonstrate continuity of insulation, areas of thermal bridging and compliance with Building Regulations should include the following:

- Thermal anomalies.
- Differentiate between real thermal anomalies, where temperature differences are caused by deficiencies in thermal insulation, and those that occur through confounding factors such as localised differences in air movement, reflection and emissivity.
- Quantify affected areas in relation to the total insulated areas.
- State whether the anomalies and the building thermal insulation as a whole are acceptable.

13.3.8.4 Quantitative appraisal of thermal anomalies

A thermographic survey will show differences in apparent temperature of areas within the field of view. To be useful, however, it must systematically detect all the apparent defects; assess them against a predetermined set of criteria; reliably discount those anomalies that are not real defects; evaluate those that are real defects, and report the results to the client.

13.3.8.4.1 Selection of critical temperature parameter

The BRE information Paper IP17/01 (Information Paper IP17/01, Assessing the Effects of Thermal Bridging at Junctions and Around Openings. Tim Ward, BRE, 2001) provides useful guidance on minimum acceptable internal surface temperatures and appropriate values of Critical Surface Temperature Factor, f_{CRsi}. The use of a surface temperature factor allows surveys under any thermal conditions to show areas that are at risk of condensation or mould growth under design conditions.

The actual surface temperature will depend greatly on the temperatures inside and outside at the time of the survey, but a ‘Surface Temperature Factor’ (f_{Rsi}) has been devised that is independent of the absolute conditions. It is a ratio of temperature drop across the building fabric to the total temperature drop between inside and outside air.

For internal surveys: $f_{Rsi} = (T_{si} – T_e)/(T_i – T_e)$

T_{si} = internal surface temperature
T_i = internal air temperature
T_e = external air temperature

A value for f_{CRsi} of 0.75 is considered appropriate across new building as the upper end usage is not a factor considered in testing for 'Continuity of Insulation', or 'Thermal Bridging'. However, when considering refurbished or extended buildings, for example swimming pools, internal surveys may need to account for unusal circumstances.

13.3.8.4.2 Alternative method using only surface temperatures

There are strong arguments for basing thermographic surveys on surface temperatures alone, with no need to measure air temperature.

- Stratification inside the building makes reference to air internal temperatures very difficult. Is it mean air temperature, low level, high level or temperature at the level of the anomaly and how far from the wall should it be measured?
- Radiation effects, such as radiation to the night sky, make use of of external air temperature difficult. It is not unusual for the outside surface of building fabric to be below air temperature because of radiation to the sky which may be as low as –50°C (–58°F). This can be seen with the naked eye by the fact that dew and frost often appear on building surfaces even when the air temperature does not drop below the dewpoint.
- It should be noted that the concept of U values is based on 'environmental temperatures' on each side of the structure. This is neglected by many inexperienced analysts.
- The two temperatures that are firmly related to the transfer of heat through building fabric (and any solid) are the surface temperatures on each side.
- Therefore, by referring to surface temperatures the survey is more repeatable.
- The surface temperatures used are the averages of surface temperatures on the same material in an area near the anomaly on the inside and the outside of the fabric. Together with the temperature of the anomaly, a threshold level can be set dependent on these temperatures using the critical surface temperature factor.
- These arguments do not obviate the need for the thermographer to beware of reflections of objects at unusual temperatures in the background facing the building fabric surfaces.
- The thermographer should also use a comparison between external faces facing different directions to determine whether there is residual heat from solar gain affecting the external surfaces.
- External surveys should not be conducted on a surface where $T_{si} - T_{so}$ on the face is more than 10% greater than $T_{si} - T_{so}$ on the north or nearest to north face.
- For a defect that causes a failure under the 0.75 condition of IP17/01 the critical surface factors are 0.78 on the inside surface and 0.93 on the outside surface.

The table below shows the internal and external surface temperatures at an anomaly which would lead to failure under IP17/01. It also shows the deterioration in thermal insulation that is necessary to cause this.

Example for lightweight built-up cladding with defective insulation	**Good area**	**Failing area**
Outside temperature in °C	0	0
Inside surface temperature in °C	19.1	15.0
Outside surface temperature in °C	0.3	1.5
Surface factor from IP17/01	0.95	0.75
Critical external surface temperature factor, after IP17/01		0.92
Insulation thickness to give this level of performance, mm	80	5.1
Local U value W/m^{2}K	0.35	1.92
UKTA TN1 surface factor		0.78
UKTA TN1 surface factor outside		0.93

Notes to the table

1 Values of surface resistances taken from ADL2 2001, are:

- Inside surface 0.13 m^{2}K/W
- Outside surface 0.04 m^{2}K/W

These originate from BS EN ISO 6946 (BN EN ISO 6946:1997 Building components and building elements - Thermal resistance and thermal transmittance - Calculation method).

2 Thermal insulation used here is assumed to have a conductivity of 0.03 W/m K.

3 The difference in temperature between an anomaly and the good areas is 1.2 degrees on the outside and 4.1 degrees on the inside.

4 The UKTA TN1 surface temperature factor for internal surveys is:
$F_{si} = (T_{sia} - T_{so})/(T_{si} - T_{so})$
where:
T_{sia} = internal surface temperature at anomaly
T_{so} = external surface temperature (good area)
T_{si} = internal surface temperature (good area)

5 The UKTA TN1 surface temperature factor for external surveys is:
$F_{so} = (T_{soa} - T_{si})/(T_{so} - T_{si})$
where T_{soa} = external surface temperature at anomaly

13.3.8.4.3 Selecting maximum acceptable defect area

The allowable area of defect is a quality control issue. It can be argued that there should be no area on which condensation, mould growth or defective insulation will occur and any such anomalies should be included in the report. However, a commonly

used value of 0.1% of the building exposed surface area is generally accepted as the maximum combined defect area allowable to comply with the Building Regulations. This represents one square metre in every thousand.

13.3.8.4.4 Measuring surface temperature

Measurement of surface temperature is the function of the infrared imaging system. The trained thermographer will recognise, account for and report on the variation of emissivity and reflectivity of the surfaces under consideration.

13.3.8.4.5 Measuring area of the defects

Measurement of defect area can be performed by pixel counting in the thermal analysis software or most spreadhseet packages provided that:

- the distance from camera to object is accurately measured probably using a laser measurement system,
- the target distance should take into account the IFOV of the imaging system,
- any angular change between the camera and the object surface from the perpendicular is accounted for.

Buildings consist of numerous construction features that are not conducive to quantitative surveys including windows, roof lights, luminaries, heat emitters, cooling equipment, service pipes and electrical conductors. However, the joints and connections between these objects and the building envelope should be considered as part of the survey.

13.3.8.5 Conditions and equipment

To achieve best results from a thermal insulation survey it is important to consider the environmental conditions and to use the most appropriate thermographic technique for the task.

Thermal anomalies will only present themselves to the thermographer where temperature differences exist and environmental phenomena are accounted for. As a minimum, the following conditions should be complied with:

- Temperature differences across the building fabric to be greater than 10°C (18°F).
- Internal air to ambient air temperature difference to be greater than 5°C (9°F) for the last twentyfour hours before survey.
- External air temperature to be within ±3°C (±5.4°F) for duration of survey and for the previous hour.
- External air temperature to be within ±10°C (±18°F) for the preceding twentyfour hours.

In addition, external surveys should also comply with the following:

- Necessary surfaces free from direct solar radiation and the residual effects of past solar radiation. This can be checked by comparing the surface temperatures of opposite sides of the building.
- No precipitation either just prior to or during the survey.
- Ensure all building surfaces to be inspected are dry.
- Wind speed to be less than 10 metres / second (19.5 kn.).

As well as temperature, there are other environmental conditions that should also be taken into account when planning a thermographic building survey. External inspections, for example, may be influenced by radiation emissions and reflections from adjacent buildings or a cold clear sky, and even more significantly the heating effect that the sun may have on surface.

Additionally, where background temperatures differ from air temperatures either internally or externally by more than 5 K, then background temperatures should be measured on all effected surfaces to allow surface temperature to be measured with sufficient accuracy.

13.3.8.6 Survey and analysis

The following provides some operational guidance to the thermographic operator.

The survey must collect sufficient thermographic information to demonstrate that all surfaces have been inspected in order that all thermal anomalies are reported and evaluated.

Initially, environmental data must be collected, as with any thermographic survey including:

- Internal temperature in the region of the anomaly.
- External temperature in the region of the anomaly.
- Emissivity of the surface.
- Background temperature.
- Distance from the surface.

By interpolation, determine the threshold temperature to be used.

- For internal surveys the threshold surface temperature (T_{sia}) is $T_{sia} = f_{si}(T_{si} - T_{so}) + T_{so}$. The thermographer will be looking for evidence of surface temperature below this threshold.
- For external surveys the threshold temperature (T_{soa}) is $T_{soa} = f_{so}(T_{so} - T_{si}) + T_{si}$. The thermographer will be looking for evidence of surface temperature above this threshold.

Images of anomalies must be captured in such a way that they are suitable for analysis:

- The image is square to any features of the wall or roof.

- The viewing angle is nearly perpendicular to the surface being imaged. Interfering sources of infrared radiation such as lights, heat emitters, electric conductors, reflective elements are minimised.

The method of analysis will depend somewhat on analysis software used, but the key stages are as follows:

Produce an image of each anomaly or cluster of anomalies.

- Use a software analysis tool to enclose the anomalous area within the image, taking care not to include construction details that are to be excluded.
- Calculate the area below the threshold temperature for internal surveys or above the threshold temperature for external surveys. This is the defect area. Some anomalies that appeared to be defects at the time of the survey may not show defect areas at this stage.
- Add the defect areas from all the images $\sum A_d$.
- Calculate the total area of exposed building fabric. This is the surface area of all the walls and roof. It is conventional to use the external surface area. For a simple shape building this is calculated from overall width, length and height.
  $A_t = (2h(L + w)) + (Lw)$
- Identify the critical defect area A_c. Provisionally this is set at one thousandth or 0.1% of the total surface area.
  $A_c = A_t/1000$
- If $\sum A_d < A_c$ the building as a whole can be considered to have 'reasonably continuous' insulation.

13.3.8.7 Reporting

Reports should certificate a pass/fail result, comply with customers requirements and as a minimum include the information required by BSEN 13187. The following data is normally required so that survey can be repeated following remedial action.

- Background to the objective and principles of the test.
- Location, orientation, date and time of survey.
- A unique identifying reference.
- Thermographer's name and qualifications.
- Type of construction.
- Weather conditions, wind speed and direction, last precipitation, sunshine, degree of cloud cover.
- Ambient temperatures inside and outside before, at the beginning of survey and the time of each image. Air temperature and radiant temperature should be recorded.
- Statement of any deviation from relevant test requirements.
- Equipment used, last calibration date, any knows defects.
- Name, affiliation and qualifications of tester.

- Type, extent and position of each observed defect.
- Results of any supplementary measurements and investigations.
- Reports should be indexed and archived by thermographers.

13.3.8.7.1 Considerations and limitations

The choice between internal and external surveys will depend on:

- Access to the surface. Buildings where both the internal and the external surfaces are obscured, e.g., by false ceilings racking or materials stacked against walls may not be amenable to this type of survey.
- Location of the thermal insulation. Surveys are usually more effective from the side nearest to the thermal insulation.
- Location of heavyweight materials. Surveys are usually less effective from the side nearest to the heavyweight material.
- The purpose of the survey. If the survey aims to show risk of condensation and mould growth it should be internal.
- Location of glass, bare metal or other materials that may be highly reflective. Surveys are usually less effective on highly reflective surfaces.
- A defect will usually produce a smaller temperature difference on the outside of a wall exposed to external air movement. However, missing or defective insulation near the external surface can often be more readily indentified externally.

13.4 Disclaimer

13.4.1 Copyright notice

Some sections and/or images appearing in this chapter are copyrighted to the following organizations and companies:

- FORMAS—The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, Stockholm, Sweden
- ITC—Infrared Training Center, Boston, MA, United States
- Stockton Infrared Thermographic Services, Inc., Randleman, NC, United States
- Professional Investigative Engineers, Westminster, CO, United States
- United Kingdom Thermography Association (UKTA)

13.4.2 Training & certification

Carrying out building thermography inspections requires substantial training and experience, and may require certification from a national or regional standardization body. This section is provided only as an introduction to building thermography. The user is strongly recommended to attend relevant training courses.

For more information about infrared training, visit the following website:

http://www.infraredtraining.com

13.4.3 National or regional building codes

The commented building structures in this chapter may differ in construction from country to country. For more information about construction details and standards of procedure, always consult national or regional building codes.

14 About FLIR Systems

FLIR Systems was established in 1978 to pioneer the development of high-performance infrared imaging systems, and is the world leader in the design, manufacture, and marketing of thermal imaging systems for a wide variety of commercial, industrial, and government applications. Today, FLIR Systems embraces four major companies with outstanding achievements in infrared technology since 1965—the Swedish AGEMA Infrared Systems (formerly AGA Infrared Systems), and the three United States companies Indigo Systems, FSI, and Inframetrics.

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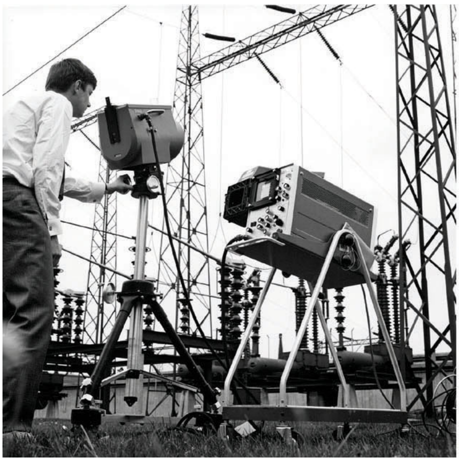

Figure 14.1 LEFT: Thermovision® Model 661 from 1969. The camera weighed approximately 25 kg (55 lb.), the oscilloscope 20 kg (44 lb.), and the tripod 15 kg (33 lb.). The operator also needed a 220 VAC generator set, and a 10 L (2.6 US gallon) jar with liquid nitrogen. To the left of the oscilloscope the Polaroid attachment (6 kg/13 lb.) can be seen. **RIGHT:** FLIR i5 from 2008. Weight: 0.34 kg (0.75 lb.), including the battery

The company has sold more than 40,000 infrared cameras worldwide for applications such as predictive maintenance, R & D, non-destructive testing, process control and automation, and machine vision, among many others.

FLIR Systems has three manufacturing plants in the United States (Portland, OR, Boston, MA, Santa Barbara, CA) and one in Sweden (Stockholm). Direct sales offices in Belgium, Brazil, China, France, Germany, Great Britain, Hong Kong, Italy, Japan, Sweden, and the USA—together with a worldwide network of agents and distributors—support our international customer base.

FLIR Systems is at the forefront of innovation in the infrared camera industry. We anticipate market demand by constantly improving our existing cameras and developing new ones. The company has set milestones in product design and development such as the introduction of the first battery-operated portable camera for industrial inspections, and the first uncooled infrared camera, to mention just two innovations.

FLIR Systems manufactures all vital mechanical and electronic components of the camera systems itself. From detector design and manufacturing, to lenses and system electronics, to final testing and calibration, all production steps are carried out and supervised by our own engineers. The in-depth expertise of these infrared specialists ensures the accuracy and reliability of all vital components that are assembled into your infrared camera.

14.1 More than just an infrared camera

At FLIR Systems we recognize that our job is to go beyond just producing the best infrared camera systems. We are committed to enabling all users of our infrared camera systems to work more productively by providing them with the most powerful camera–software combination. Especially tailored software for predictive maintenance, R & D, and process monitoring is developed in-house. Most software is available in a wide variety of languages.

We support all our infrared cameras with a wide variety of accessories to adapt your equipment to the most demanding infrared applications.

14.2 Sharing our knowledge

Although our cameras are designed to be very user-friendly, there is a lot more to thermography than just knowing how to handle a camera. Therefore, FLIR Systems has founded the Infrared Training Center (ITC), a separate business unit, that provides certified training courses. Attending one of the ITC courses will give you a truly hands-on learning experience.

The staff of the ITC are also there to provide you with any application support you may need in putting infrared theory into practice.

14.3 Supporting our customers

FLIR Systems operates a worldwide service network to keep your camera running at all times. If you discover a problem with your camera, local service centers have all the equipment and expertise to solve it within the shortest possible time. Therefore, there is no need to send your camera to the other side of the world or to talk to someone who does not speak your language.

14.4 A few images from our facilities

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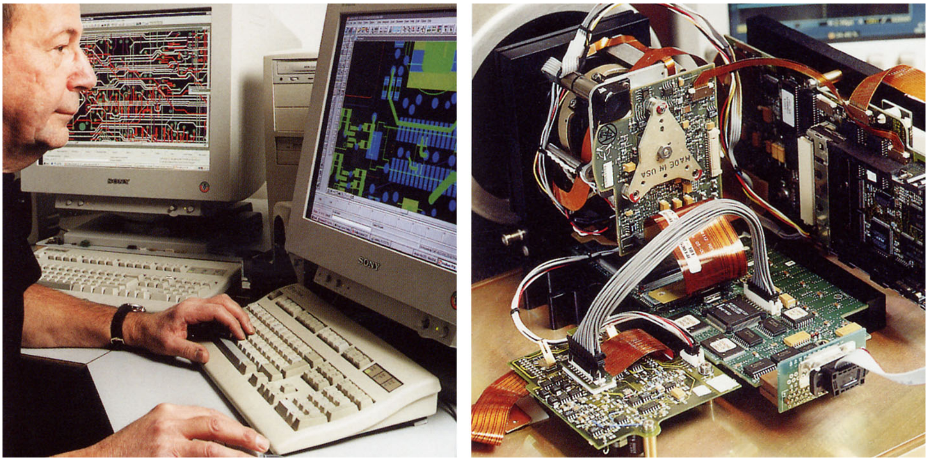

Figure 14.2 **LEFT:** Development of system electronics; **RIGHT:** Testing of an FPA detector

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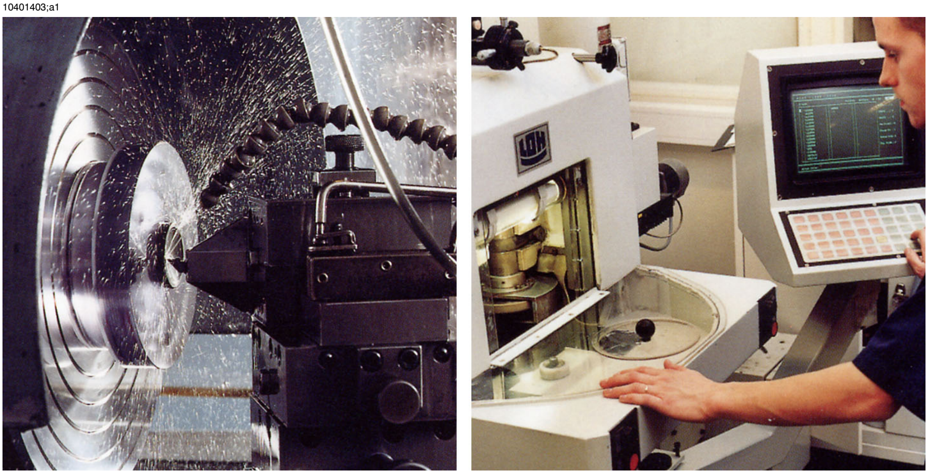


Figure 14.3 **LEFT:** Diamond turning machine; **RIGHT:** Lens polishing

10401503;a1

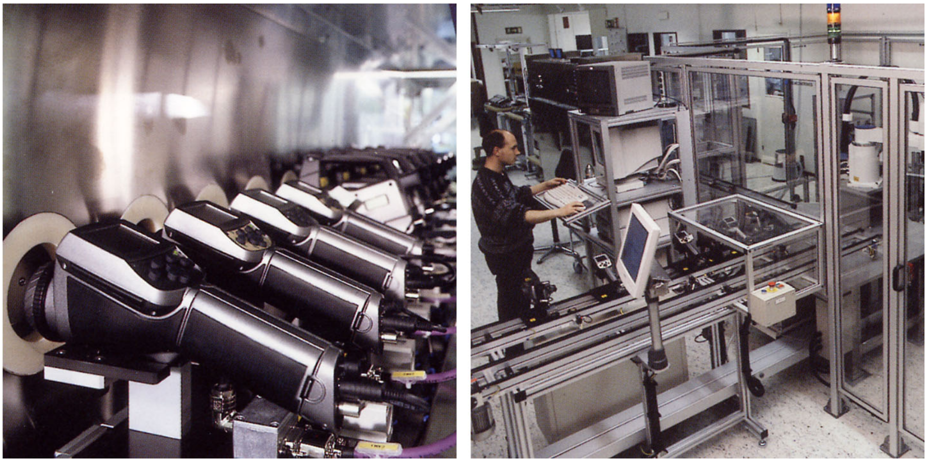


Figure 14.4 LEFT: Testing of infrared cameras in the climatic chamber; **RIGHT:** Robot used for camera testing and calibration

15 Glossary

Term or expression	Explanation
absorption (absorption factor)	The amount of radiation absorbed by an object relative to the received radiation. A number between 0 and 1.
atmosphere	The gases between the object being measured and the camera, normally air.
autoadjust	A function making a camera perform an internal image correction.
autopalette	The IR image is shown with an uneven spread of colors, displaying cold objects as well as hot ones at the same time.
blackbody	Totally non-reflective object. All its radiation is due to its own temperature.
blackbody radiator	An IR radiating equipment with blackbody properties used to calibrate IR cameras.
calculated atmospheric transmission	A transmission value computed from the temperature, the relative humidity of air and the distance to the object.
cavity radiator	A bottle shaped radiator with an absorbing inside, viewed through the bottleneck.
color temperature	The temperature for which the color of a blackbody matches a specific color.
conduction	The process that makes heat diffuse into a material.
continuous adjust	A function that adjusts the image. The function works all the time, continuously adjusting brightness and contrast according to the image content.
convection	Convection is a heat transfer mode where a fluid is brought into motion, either by gravity or another force, thereby transferring heat from one place to another.
dual isotherm	An isotherm with two color bands, instead of one.
emissivity (emissivity factor)	The amount of radiation coming from an object, compared to that of a blackbody. A number between 0 and 1.
emittance	Amount of energy emitted from an object per unit of time and area (W/m^2)
environment	Objects and gases that emit radiation towards the object being measured.
estimated atmospheric transmission	A transmission value, supplied by a user, replacing a calculated one

Term or expression	Explanation
external optics	Extra lenses, filters, heat shields etc. that can be put between the camera and the object being measured.
filter	A material transparent only to some of the infrared wavelengths.
FOV	Field of view: The horizontal angle that can be viewed through an IR lens.
FPA	Focal plane array: A type of IR detector.
graybody	An object that emits a fixed fraction of the amount of energy of a blackbody for each wavelength.
IFOV	Instantaneous field of view: A measure of the geometrical resolution of an IR camera.
image correction (internal or external)	A way of compensating for sensitivity differences in various parts of live images and also of stabilizing the camera.
infrared	Non-visible radiation, having a wavelength from about 2–13 μm.
IR	infrared
isotherm	A function highlighting those parts of an image that fall above, below or between one or more temperature intervals.
isothermal cavity	A bottle-shaped radiator with a uniform temperature viewed through the bottleneck.
Laser LocatIR	An electrically powered light source on the camera that emits laser radiation in a thin, concentrated beam to point at certain parts of the object in front of the camera.
laser pointer	An electrically powered light source on the camera that emits laser radiation in a thin, concentrated beam to point at certain parts of the object in front of the camera.
level	The center value of the temperature scale, usually expressed as a signal value.
manual adjust	A way to adjust the image by manually changing certain parameters.
NETD	Noise equivalent temperature difference. A measure of the image noise level of an IR camera.
noise	Undesired small disturbance in the infrared image
object parameters	A set of values describing the circumstances under which the measurement of an object was made, and the object itself (such as emissivity, reflected apparent temperature, distance etc.)
object signal	A non-calibrated value related to the amount of radiation received by the camera from the object.

Term or expression	Explanation
palette	The set of colors used to display an IR image.
pixel	Stands for *picture element*. One single spot in an image.
radiance	Amount of energy emitted from an object per unit of time, area and angle ($W/m^2/sr$)
radiant power	Amount of energy emitted from an object per unit of time (W)
radiation	The process by which electromagnetic energy, is emitted by an object or a gas.
radiator	A piece of IR radiating equipment.
range	The current overall temperature measurement limitation of an IR camera. Cameras can have several ranges. Expressed as two blackbody temperatures that limit the current calibration.
reference temperature	A temperature which the ordinary measured values can be compared with.
reflection	The amount of radiation reflected by an object relative to the received radiation. A number between 0 and 1.
relative humidity	Relative humidity represents the ratio between the current water vapour mass in the air and the maximum it may contain in saturation conditions.
saturation color	The areas that contain temperatures outside the present level/span settings are colored with the saturation colors. The saturation colors contain an 'overflow' color and an 'underflow' color. There is also a third red saturation color that marks everything saturated by the detector indicating that the range should probably be changed.
span	The interval of the temperature scale, usually expressed as a signal value.
spectral (radiant) emittance	Amount of energy emitted from an object per unit of time, area and wavelength ($W/m^2/\mu m$)
temperature difference, or difference of temperature.	A value which is the result of a subtraction between two temperature values.
temperature range	The current overall temperature measurement limitation of an IR camera. Cameras can have several ranges. Expressed as two blackbody temperatures that limit the current calibration.
temperature scale	The way in which an IR image currently is displayed. Expressed as two temperature values limiting the colors.
thermogram	infrared image

Term or expression	Explanation
transmission (or transmittance) factor	Gases and materials can be more or less transparent. Transmission is the amount of IR radiation passing through them. A number between 0 and 1.
transparent isotherm	An isotherm showing a linear spread of colors, instead of covering the highlighted parts of the image.
visual	Refers to the video mode of a IR camera, as opposed to the normal, thermographic mode. When a camera is in video mode it captures ordinary video images, while thermographic images are captured when the camera is in IR mode.

16 Thermographic measurement techniques

16.1 Introduction

An infrared camera measures and images the emitted infrared radiation from an object. The fact that radiation is a function of object surface temperature makes it possible for the camera to calculate and display this temperature.

However, the radiation measured by the camera does not only depend on the temperature of the object but is also a function of the emissivity. Radiation also originates from the surroundings and is reflected in the object. The radiation from the object and the reflected radiation will also be influenced by the absorption of the atmosphere.

To measure temperature accurately, it is therefore necessary to compensate for the effects of a number of different radiation sources. This is done on-line automatically by the camera. The following object parameters must, however, be supplied for the camera:

- The emissivity of the object
- The reflected apparent temperature
- The distance between the object and the camera
- The relative humidity
- Temperature of the atmosphere

16.2 Emissivity

The most important object parameter to set correctly is the emissivity which, in short, is a measure of how much radiation is emitted from the object, compared to that from a perfect blackbody of the same temperature.

Normally, object materials and surface treatments exhibit emissivity ranging from approximately 0.1 to 0.95. A highly polished (mirror) surface falls below 0.1, while an oxidized or painted surface has a higher emissivity. Oil-based paint, regardless of color in the visible spectrum, has an emissivity over 0.9 in the infrared. Human skin exhibits an emissivity 0.97 to 0.98.

Non-oxidized metals represent an extreme case of perfect opacity and high reflexivity, which does not vary greatly with wavelength. Consequently, the emissivity of metals is low – only increasing with temperature. For non-metals, emissivity tends to be high, and decreases with temperature.

16.2.1 Finding the emissivity of a sample

16.2.1.1 Step 1: Determining reflected apparent temperature

Use one of the following two methods to determine reflected apparent temperature:

16.2.1.1.1 Method 1: Direct method

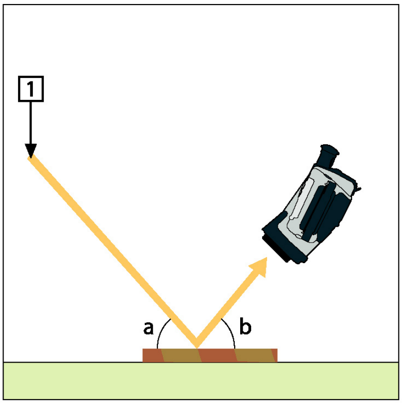
<table>
<tr><td>1</td><td>Look for possible reflection sources, considering that the incident angle = reflection angle (a = b).
10588903;a1


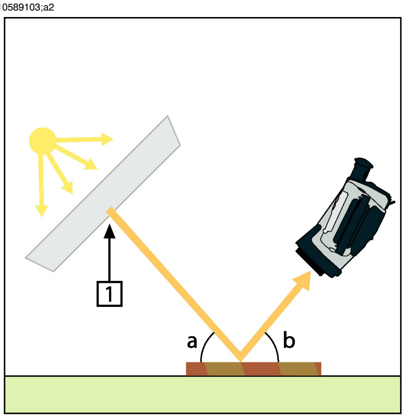
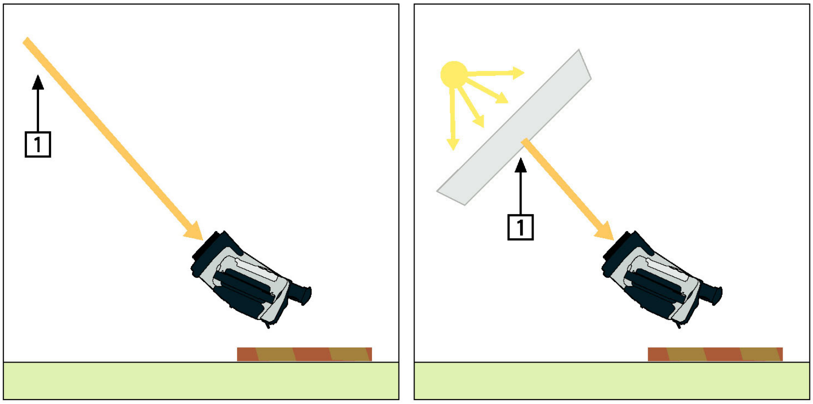
Figure 16.1 1 = Reflection source</td></tr>
<tr><td>2</td><td>If the reflection source is a spot source, modify the source by obstructing it using a piece if cardboard.
10589103;a2


Figure 16.2 1 = Reflection source</td></tr>
</table>

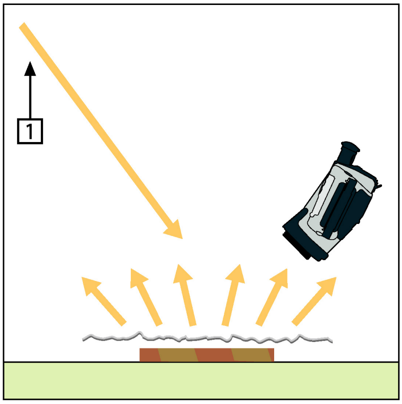
3	Measure the radiation intensity (= apparent temperature) from the reflecting source using the following settings: ■ Emissivity: 1.0 ■ D_{obj}: 0 You can measure the radiation intensity using one of the following two methods: 10589003;a2  **Figure 16.3** 1 = Reflection source

Note: Using a thermocouple to measure reflected apparent temperature is not recommended for two important reasons:

- A thermocouple does not measure radiation intensity
- A thermocouple requires a very good thermal contact to the surface, usually by gluing and covering the sensor by a thermal isolator.

16.2.1.1.2 Method 2: Reflector method

1	Crumble up a large piece of aluminum foil.
2	Uncrumble the aluminum foil and attach it to a piece of cardboard of the same size.
3	Put the piece of cardboard in front of the object you want to measure. Make sure that the side with aluminum foil points to the camera.
4	Set the emissivity to 1.0.

5	Measure the apparent temperature of the aluminum foil and write it down. 10727003;a2  **Figure 16.4** Measuring the apparent temperature of the aluminum foil

16.2.1.2 Step 2: Determining the emissivity

1	Select a place to put the sample.
2	Determine and set reflected apparent temperature according to the previous procedure.
3	Put a piece of electrical tape with known high emissivity on the sample.
4	Heat the sample at least 20 K above room temperature. Heating must be reasonably even.
5	Focus and auto-adjust the camera, and freeze the image.
6	Adjust **Level** and **Span** for best image brightness and contrast.
7	Set emissivity to that of the tape (usually 0.97).
8	Measure the temperature of the tape using one of the following measurement functions: ■ **Isotherm** (helps you to determine both the temperature and how evenly you have heated the sample) ■ **Spot** (simpler) ■ **Box Avg** (good for surfaces with varying emissivity).
9	Write down the temperature.
10	Move your measurement function to the sample surface.
11	Change the emissivity setting until you read the same temperature as your previous measurement.
12	Write down the emissivity.

Note:

- Avoid forced convection
- Look for a thermally stable surrounding that will not generate spot reflections
- Use high quality tape that you know is not transparent, and has a high emissivity you are certain of
- This method assumes that the temperature of your tape and the sample surface are the same. If they are not, your emissivity measurement will be wrong.

16.3 Reflected apparent temperature

This parameter is used to compensate for the radiation reflected in the object. If the emissivity is low and the object temperature relatively far from that of the reflected it will be important to set and compensate for the reflected apparent temperature correctly.

16.4 Distance

The distance is the distance between the object and the front lens of the camera. This parameter is used to compensate for the following two facts:

- That radiation from the target is absorbed by the athmosphere between the object and the camera.
- That radiation from the atmosphere itself is detected by the camera.

16.5 Relative humidity

The camera can also compensate for the fact that the transmittance is also dependent on the relative humidity of the atmosphere. To do this set the relative humidity to the correct value. For short distances and normal humidity the relative humidity can normally be left at a default value of 50%.

16.6 Other parameters

In addition, some cameras and analysis programs from FLIR Systems allow you to compensate for the following parameters:

- Atmospheric temperature – *i.e.* the temperature of the atmosphere between the camera and the target
- External optics temperature – *i.e.* the temperature of any external lenses or windows used in front of the camera
- External optics transmittance – *i.e.* the transmission of any external lenses or windows used in front of the camera

17 History of infrared technology

Before the year 1800, the existence of the infrared portion of the electromagnetic spectrum wasn't even suspected. The original significance of the infrared spectrum, or simply 'the infrared' as it is often called, as a form of heat radiation is perhaps less obvious today than it was at the time of its discovery by Herschel in 1800.

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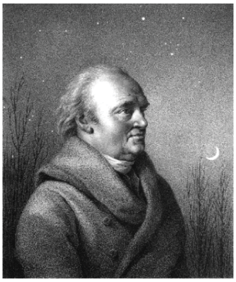

Figure 17.1 Sir William Herschel (1738–1822)

The discovery was made accidentally during the search for a new optical material. Sir William Herschel – Royal Astronomer to King George III of England, and already famous for his discovery of the planet Uranus – was searching for an optical filter material to reduce the brightness of the sun's image in telescopes during solar observations. While testing different samples of colored glass which gave similar reductions in brightness he was intrigued to find that some of the samples passed very little of the sun's heat, while others passed so much heat that he risked eye damage after only a few seconds' observation.

Herschel was soon convinced of the necessity of setting up a systematic experiment, with the objective of finding a single material that would give the desired reduction in brightness as well as the maximum reduction in heat. He began the experiment by actually repeating Newton's prism experiment, but looking for the heating effect rather than the visual distribution of intensity in the spectrum. He first blackened the bulb of a sensitive mercury-in-glass thermometer with ink, and with this as his radiation detector he proceeded to test the heating effect of the various colors of the spectrum formed on the top of a table by passing sunlight through a glass prism. Other thermometers, placed outside the sun's rays, served as controls.

As the blackened thermometer was moved slowly along the colors of the spectrum, the temperature readings showed a steady increase from the violet end to the red end. This was not entirely unexpected, since the Italian researcher, Landriani, in a similar experiment in 1777 had observed much the same effect. It was Herschel,

however, who was the first to recognize that there must be a point where the heating effect reaches a maximum, and that measurements confined to the visible portion of the spectrum failed to locate this point.

10398903;a1

Figure 17.2 Marsilio Landriani (1746–1815)

Moving the thermometer into the dark region beyond the red end of the spectrum, Herschel confirmed that the heating continued to increase. The maximum point, when he found it, lay well beyond the red end – in what is known today as the 'infrared wavelengths'.

When Herschel revealed his discovery, he referred to this new portion of the electromagnetic spectrum as the 'thermometrical spectrum'. The radiation itself he sometimes referred to as 'dark heat', or simply 'the invisible rays'. Ironically, and contrary to popular opinion, it wasn't Herschel who originated the term 'infrared'. The word only began to appear in print around 75 years later, and it is still unclear who should receive credit as the originator.

Herschel's use of glass in the prism of his original experiment led to some early controversies with his contemporaries about the actual existence of the infrared wavelengths. Different investigators, in attempting to confirm his work, used various types of glass indiscriminately, having different transparencies in the infrared. Through his later experiments, Herschel was aware of the limited transparency of glass to the newly-discovered thermal radiation, and he was forced to conclude that optics for the infrared would probably be doomed to the use of reflective elements exclusively (i.e. plane and curved mirrors). Fortunately, this proved to be true only until 1830, when the Italian investigator, Melloni, made his great discovery that naturally occurring rock salt (NaCl) – which was available in large enough natural crystals to be made into lenses and prisms – is remarkably transparent to the infrared. The result was that rock salt became the principal infrared optical material, and remained so for the next hundred years, until the art of synthetic crystal growing was mastered in the 1930's.

10399103;a1

Figure 17.3 Macedonio Melloni (1798–1854)

Thermometers, as radiation detectors, remained unchallenged until 1829, the year Nobili invented the thermocouple. (Herschel's own thermometer could be read to 0.2 °C (0.036 °F), and later models were able to be read to 0.05 °C (0.09 °F)). Then a breakthrough occurred; Melloni connected a number of thermocouples in series to form the first thermopile. The new device was at least 40 times as sensitive as the best thermometer of the day for detecting heat radiation – capable of detecting the heat from a person standing three meters away.

The first so-called 'heat-picture' became possible in 1840, the result of work by Sir John Herschel, son of the discoverer of the infrared and a famous astronomer in his own right. Based upon the differential evaporation of a thin film of oil when exposed to a heat pattern focused upon it, the thermal image could be seen by reflected light where the interference effects of the oil film made the image visible to the eye. Sir John also managed to obtain a primitive record of the thermal image on paper, which he called a 'thermograph'.

10399003;a2

Figure 17.4 Samuel P. Langley (1834–1906)

The improvement of infrared-detector sensitivity progressed slowly. Another major breakthrough, made by Langley in 1880, was the invention of the bolometer. This consisted of a thin blackened strip of platinum connected in one arm of a Wheatstone bridge circuit upon which the infrared radiation was focused and to which a sensitive galvanometer responded. This instrument is said to have been able to detect the heat from a cow at a distance of 400 meters.

An English scientist, Sir James Dewar, first introduced the use of liquefied gases as cooling agents (such as liquid nitrogen with a temperature of -196 °C (-320.8 °F)) in low temperature research. In 1892 he invented a unique vacuum insulating container in which it is possible to store liquefied gases for entire days. The common 'thermos bottle', used for storing hot and cold drinks, is based upon his invention.

Between the years 1900 and 1920, the inventors of the world 'discovered' the infrared. Many patents were issued for devices to detect personnel, artillery, aircraft, ships – and even icebergs. The first operating systems, in the modern sense, began to be developed during the 1914–18 war, when both sides had research programs devoted to the military exploitation of the infrared. These programs included experimental systems for enemy intrusion/detection, remote temperature sensing, secure communications, and 'flying torpedo' guidance. An infrared search system tested during this period was able to detect an approaching airplane at a distance of 1.5 km (0.94 miles), or a person more than 300 meters (984 ft.) away.

The most sensitive systems up to this time were all based upon variations of the bolometer idea, but the period between the two wars saw the development of two revolutionary new infrared detectors: the image converter and the photon detector. At first, the image converter received the greatest attention by the military, because it enabled an observer for the first time in history to literally 'see in the dark'. However, the sensitivity of the image converter was limited to the near infrared wavelengths, and the most interesting military targets (i.e. enemy soldiers) had to be illuminated by infrared search beams. Since this involved the risk of giving away the observer's position to a similarly-equipped enemy observer, it is understandable that military interest in the image converter eventually faded.

The tactical military disadvantages of so-called 'active' (i.e. search beam-equipped) thermal imaging systems provided impetus following the 1939–45 war for extensive secret military infrared-research programs into the possibilities of developing 'passive' (no search beam) systems around the extremely sensitive photon detector. During this period, military secrecy regulations completely prevented disclosure of the status of infrared-imaging technology. This secrecy only began to be lifted in the middle of the 1950's, and from that time adequate thermal-imaging devices finally began to be available to civilian science and industry.

18 Theory of thermography

18.1 Introduction

The subjects of infrared radiation and the related technique of thermography are still new to many who will use an infrared camera. In this section the theory behind thermography will be given.

18.2 The electromagnetic spectrum

The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called *bands*, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiation in the different bands of the electromagnetic spectrum. They are all governed by the same laws and the only differences are those due to differences in wavelength.

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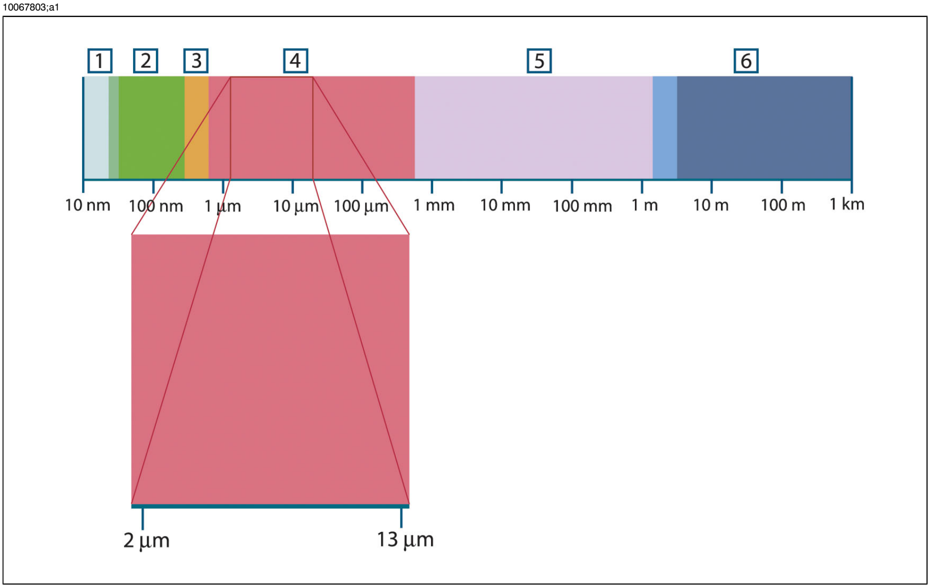

Figure 18.1 The electromagnetic spectrum. **1:** X-ray; **2:** UV; **3:** Visible; **4:** IR; **5:** Microwaves; **6:** Radiowaves.

Thermography makes use of the infrared spectral band. At the short-wavelength end the boundary lies at the limit of visual perception, in the deep red. At the long-wavelength end it merges with the microwave radio wavelengths, in the millimeter range.

The infrared band is often further subdivided into four smaller bands, the boundaries of which are also arbitrarily chosen. They include: the *near infrared* (0.75–3 µm), the *middle infrared* (3–6 µm), the *far infrared* (6–15 µm) and the *extreme infrared* (15–100

μm). Although the wavelengths are given in μm (micrometers), other units are often still used to measure wavelength in this spectral region, *e.g.* nanometer (nm) and Ångström (Å).

The relationships between the different wavelength measurements is:

$$10\ 000\ \text{Å} = 1\ 000\ \text{nm} = 1\ \mu = 1\ \mu\text{m}$$

18.3 Blackbody radiation

A blackbody is defined as an object which absorbs all radiation that impinges on it at any wavelength. The apparent misnomer *black* relating to an object emitting radiation is explained by Kirchhoff's Law (after *Gustav Robert Kirchhoff*, 1824–1887), which states that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation.

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Figure 18.2 Gustav Robert Kirchhoff (1824–1887)

The construction of a blackbody source is, in principle, very simple. The radiation characteristics of an aperture in an isotherm cavity made of an opaque absorbing material represents almost exactly the properties of a blackbody. A practical application of the principle to the construction of a perfect absorber of radiation consists of a box that is light tight except for an aperture in one of the sides. Any radiation which then enters the hole is scattered and absorbed by repeated reflections so only an infinitesimal fraction can possibly escape. The blackness which is obtained at the aperture is nearly equal to a blackbody and almost perfect for all wavelengths.

By providing such an isothermal cavity with a suitable heater it becomes what is termed a *cavity radiator*. An isothermal cavity heated to a uniform temperature generates blackbody radiation, the characteristics of which are determined solely by the temperature of the cavity. Such cavity radiators are commonly used as sources of radiation in temperature reference standards in the laboratory for calibrating thermographic instruments, such as a FLIR Systems camera for example.

If the temperature of blackbody radiation increases to more than 525°C (977°F), the source begins to be visible so that it appears to the eye no longer black. This is the incipient red heat temperature of the radiator, which then becomes orange or yellow as the temperature increases further. In fact, the definition of the so-called *color temperature* of an object is the temperature to which a blackbody would have to be heated to have the same appearance.

Now consider three expressions that describe the radiation emitted from a blackbody.

18.3.1 Planck's law

10399203;a1

Figure 18.3 Max Planck (1858–1947)

Max Planck (1858–1947) was able to describe the spectral distribution of the radiation from a blackbody by means of the following formula:

$$W_{\lambda b} = \frac{2\pi hc^2}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)} \times 10^{-6} [Watt/m^2, \mu m]$$

where:

$W_{\lambda b}$	Blackbody spectral radiant emittance at wavelength λ.
c	Velocity of light = 3 × 10^8 m/s
h	Planck's constant = 6.6 × 10^{-34} Joule sec.
k	Boltzmann's constant = 1.4 × 10^{-23} Joule/K.
T	Absolute temperature (K) of a blackbody.
λ	Wavelength (μm).

➲ The factor 10^{-6} is used since spectral emittance in the curves is expressed in Watt/m^2, μm.

Planck's formula, when plotted graphically for various temperatures, produces a family of curves. Following any particular Planck curve, the spectral emittance is zero at $\lambda = 0$, then increases rapidly to a maximum at a wavelength λ_{max} and after passing it approaches zero again at very long wavelengths. The higher the temperature, the shorter the wavelength at which maximum occurs.

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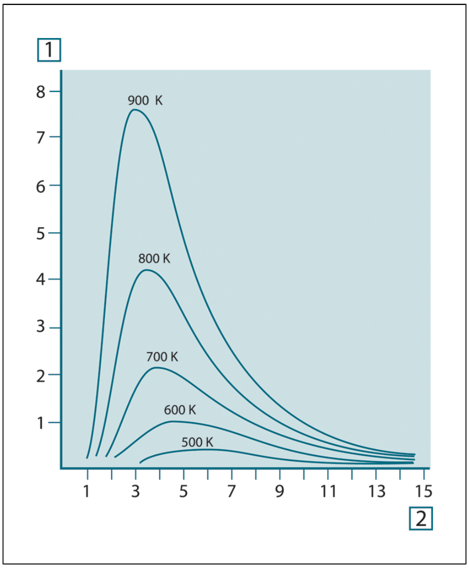

Figure 18.4 Blackbody spectral radiant emittance according to Planck's law, plotted for various absolute temperatures. **1:** Spectral radiant emittance (W/cm^2 × 10^3(μm)); **2:** Wavelength (μm)

18.3.2 Wien's displacement law

By differentiating Planck's formula with respect to λ, and finding the maximum, we have:

$$\lambda_{\max} = \frac{2898}{T}[\mu m]$$

This is Wien's formula (after *Wilhelm Wien*, 1864–1928), which expresses mathematically the common observation that colors vary from red to orange or yellow as the temperature of a thermal radiator increases. The wavelength of the color is the same as the wavelength calculated for λ_{max}. A good approximation of the value of λ_{max} for a given blackbody temperature is obtained by applying the rule-of-thumb 3 000/T

µm. Thus, a very hot star such as Sirius (11 000 K), emitting bluish-white light, radiates with the peak of spectral radiant emittance occurring within the invisible ultraviolet spectrum, at wavelength 0.27 µm.

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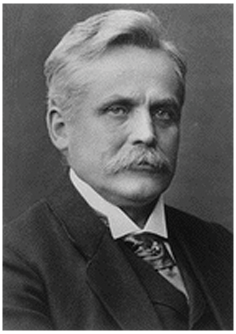

Figure 18.5 Wilhelm Wien (1864–1928)

The sun (approx. 6 000 K) emits yellow light, peaking at about 0.5 µm in the middle of the visible light spectrum.

At room temperature (300 K) the peak of radiant emittance lies at 9.7 µm, in the far infrared, while at the temperature of liquid nitrogen (77 K) the maximum of the almost insignificant amount of radiant emittance occurs at 38 µm, in the extreme infrared wavelengths.

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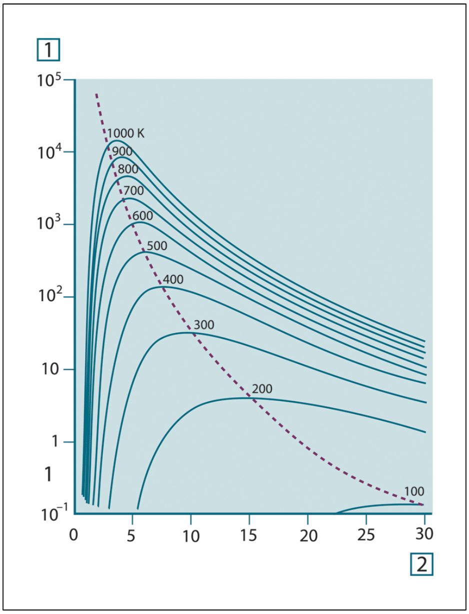

Figure 18.6 Planckian curves plotted on semi-log scales from 100 K to 1000 K. The dotted line represents the locus of maximum radiant emittance at each temperature as described by Wien's displacement law. **1:** Spectral radiant emittance (W/cm2 (μm)); **2:** Wavelength (μm).

18.3.3 Stefan-Boltzmann's law

By integrating Planck's formula from λ = 0 to λ = ∞, we obtain the total radiant emittance (W_b) of a blackbody:

$$W_b = \sigma T^4 \ [\mathrm{Watt/m^2}]$$

This is the Stefan-Boltzmann formula (after *Josef Stefan*, 1835–1893, and *Ludwig Boltzmann*, 1844–1906), which states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. Graphically, W_b represents the area below the Planck curve for a particular temperature. It can be shown that the radiant emittance in the interval λ = 0 to λ_{max} is only 25% of the total, which represents about the amount of the sun's radiation which lies inside the visible light spectrum.

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Figure 18.7 Josef Stefan (1835–1893), and Ludwig Boltzmann (1844–1906)

Using the Stefan-Boltzmann formula to calculate the power radiated by the human body, at a temperature of 300 K and an external surface area of approx. 2 m^2, we obtain 1 kW. This power loss could not be sustained if it were not for the compensating absorption of radiation from surrounding surfaces, at room temperatures which do not vary too drastically from the temperature of the body – or, of course, the addition of clothing.

18.3.4 Non-blackbody emitters

So far, only blackbody radiators and blackbody radiation have been discussed. However, real objects almost never comply with these laws over an extended wavelength region – although they may approach the blackbody behavior in certain spectral intervals. For example, a certain type of white paint may appear perfectly *white* in the visible light spectrum, but becomes distinctly *gray* at about 2 μm, and beyond 3 μm it is almost *black*.

There are three processes which can occur that prevent a real object from acting like a blackbody: a fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected, and a fraction τ may be transmitted. Since all of these factors are more or less wavelength dependent, the subscript λ is used to imply the spectral dependence of their definitions. Thus:

- The spectral absorptance α_λ= the ratio of the spectral radiant power absorbed by an object to that incident upon it.
- The spectral reflectance ρ_λ = the ratio of the spectral radiant power reflected by an object to that incident upon it.
- The spectral transmittance τ_λ = the ratio of the spectral radiant power transmitted through an object to that incident upon it.

The sum of these three factors must always add up to the whole at any wavelength, so we have the relation:

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$$

For opaque materials $\tau_\lambda = 0$ and the relation simplifies to:

$$\alpha_\lambda + \rho_\lambda = 1$$

Another factor, called the emissivity, is required to describe the fraction ε of the radiant emittance of a blackbody produced by an object at a specific temperature. Thus, we have the definition:

The spectral emissivity ε_λ= the ratio of the spectral radiant power from an object to that from a blackbody at the same temperature and wavelength.

Expressed mathematically, this can be written as the ratio of the spectral emittance of the object to that of a blackbody as follows:

$$\varepsilon_\lambda = \frac{W_{\lambda o}}{W_{\lambda b}}$$

Generally speaking, there are three types of radiation source, distinguished by the ways in which the spectral emittance of each varies with wavelength.

- A blackbody, for which $\varepsilon_\lambda = \varepsilon = 1$
- A graybody, for which $\varepsilon_\lambda = \varepsilon$ = constant less than 1
- A selective radiator, for which ε varies with wavelength

According to Kirchhoff's law, for any material the spectral emissivity and spectral absorptance of a body are equal at any specified temperature and wavelength. That is:

$$\varepsilon_\lambda = \alpha_\lambda$$

From this we obtain, for an opaque material (since $\alpha_\lambda + \rho_\lambda = 1$):

$$\varepsilon_\lambda + \rho_\lambda = 1$$

For highly polished materials ε_λ approaches zero, so that for a perfectly reflecting material (*i.e.* a perfect mirror) we have:

$$\rho_\lambda = 1$$

For a graybody radiator, the Stefan-Boltzmann formula becomes:

$$W = \varepsilon\sigma T^4 \ [\mathrm{Watt/m^2}]$$

This states that the total emissive power of a graybody is the same as a blackbody at the same temperature reduced in proportion to the value of ε from the graybody.

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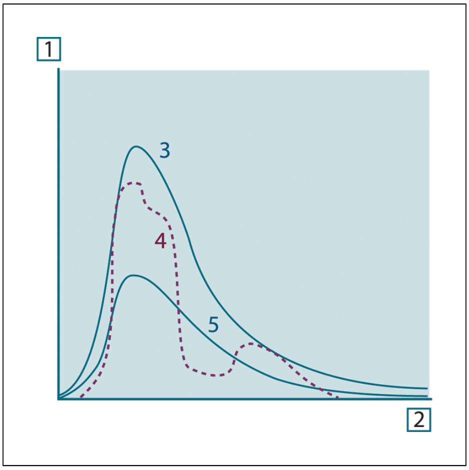

Figure 18.8 Spectral radiant emittance of three types of radiators. **1:** Spectral radiant emittance; **2:** Wavelength; **3:** Blackbody; **4:** Selective radiator; **5:** Graybody.

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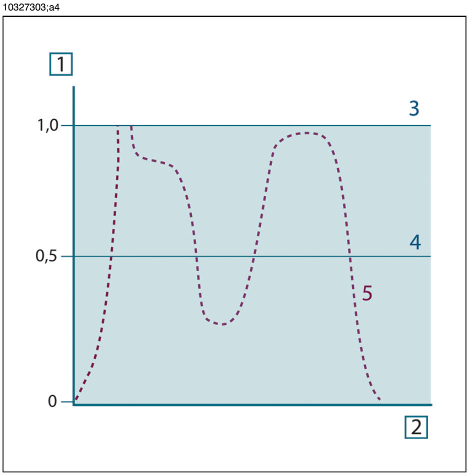

Figure 18.9 Spectral emissivity of three types of radiators. **1:** Spectral emissivity; **2:** Wavelength; **3:** Blackbody; **4:** Graybody; **5:** Selective radiator.

18.4 *Infrared semi-transparent materials*

Consider now a non-metallic, semi-transparent body – let us say, in the form of a thick flat plate of plastic material. When the plate is heated, radiation generated within its volume must work its way toward the surfaces through the material in which it is partially absorbed. Moreover, when it arrives at the surface, some of it is reflected back into the interior. The back-reflected radiation is again partially absorbed, but

some of it arrives at the other surface, through which most of it escapes; part of it is reflected back again. Although the progressive reflections become weaker and weaker they must all be added up when the total emittance of the plate is sought. When the resulting geometrical series is summed, the effective emissivity of a semi-transparent plate is obtained as:

$$\varepsilon_\lambda = \frac{(1-\rho_\lambda)(1-\tau_\lambda)}{1-\rho_\lambda\tau_\lambda}$$

When the plate becomes opaque this formula is reduced to the single formula:

$$\varepsilon_\lambda = 1-\rho_\lambda$$

This last relation is a particularly convenient one, because it is often easier to measure reflectance than to measure emissivity directly.

19 The measurement formula

As already mentioned, when viewing an object, the camera receives radiation not only from the object itself. It also collects radiation from the surroundings reflected via the object surface. Both these radiation contributions become attenuated to some extent by the atmosphere in the measurement path. To this comes a third radiation contribution from the atmosphere itself.

This description of the measurement situation, as illustrated in the figure below, is so far a fairly true description of the real conditions. What has been neglected could for instance be sun light scattering in the atmosphere or stray radiation from intense radiation sources outside the field of view. Such disturbances are difficult to quantify, however, in most cases they are fortunately small enough to be neglected. In case they are not negligible, the measurement configuration is likely to be such that the risk for disturbance is obvious, at least to a trained operator. It is then his responsibility to modify the measurement situation to avoid the disturbance e.g. by changing the viewing direction, shielding off intense radiation sources etc.

Accepting the description above, we can use the figure below to derive a formula for the calculation of the object temperature from the calibrated camera output.

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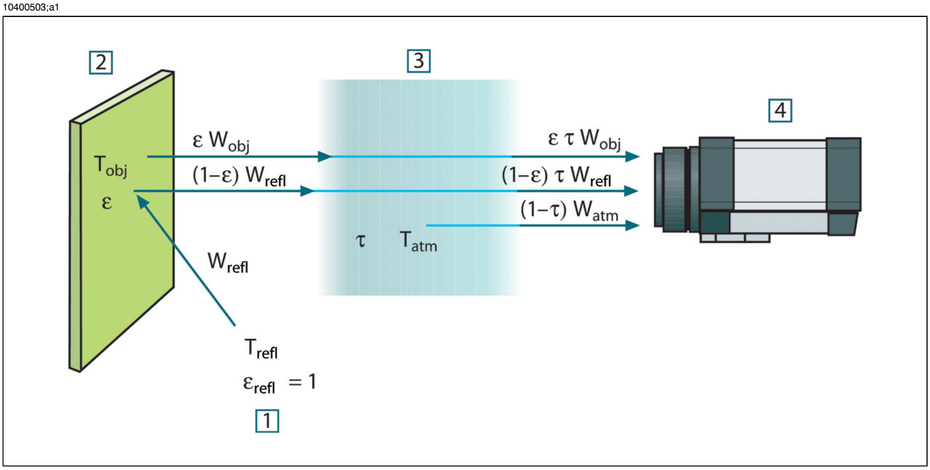

Figure 19.1 A schematic representation of the general thermographic measurement situation.**1:** Surroundings; **2:** Object; **3:** Atmosphere; **4:** Camera

Assume that the received radiation power W from a blackbody source of temperature T_{source} on short distance generates a camera output signal U_{source} that is proportional to the power input (power linear camera). We can then write (Equation 1):

$$U_{source} = CW(T_{source})$$

or, with simplified notation:

$$U_{source} = CW_{source}$$

where C is a constant.

Should the source be a graybody with emittance ε, the received radiation would consequently be εW_{source}.

We are now ready to write the three collected radiation power terms:

1 – Emission from the object = $\varepsilon\tau W_{obj}$, where ε is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{obj}.

2 – Reflected emission from ambient sources = $(1 – \varepsilon)\tau W_{refl}$, where $(1 – \varepsilon)$ is the reflectance of the object. The ambient sources have the temperature T_{refl}.

It has here been assumed that the temperature T_{refl} is the same for all emitting surfaces within the halfsphere seen from a point on the object surface. This is of course sometimes a simplification of the true situation. It is, however, a necessary simplification in order to derive a workable formula, and T_{refl} can – at least theoretically – be given a value that represents an efficient temperature of a complex surrounding.

Note also that we have assumed that the emittance for the surroundings = 1. This is correct in accordance with Kirchhoff's law: All radiation impinging on the surrounding surfaces will eventually be absorbed by the same surfaces. Thus the emittance = 1. (Note though that the latest discussion requires the complete sphere around the object to be considered.)

3 – Emission from the atmosphere = $(1 – \tau)\tau W_{atm}$, where $(1 – \tau)$ is the emittance of the atmosphere. The temperature of the atmosphere is T_{atm}.

The total received radiation power can now be written (Equation 2):

$$W_{tot} = \varepsilon\tau W_{obj} + (1-\varepsilon)\tau W_{refl} + (1-\tau)W_{atm}$$

We multiply each term by the constant C of Equation 1 and replace the CW products by the corresponding U according to the same equation, and get (Equation 3):

$$U_{tot} = \varepsilon\tau U_{obj} + (1-\varepsilon)\tau U_{refl} + (1-\tau)U_{atm}$$

Solve Equation 3 for U_{obj} (Equation 4):

$$U_{obj} = \frac{1}{\varepsilon\tau}U_{tot} - \frac{1-\varepsilon}{\varepsilon}U_{refl} - \frac{1-\tau}{\varepsilon\tau}U_{atm}$$

This is the general measurement formula used in all the FLIR Systems thermographic equipment. The voltages of the formula are:

Figure 19.2 Voltages

U_{obj}	Calculated camera output voltage for a blackbody of temperature T_{obj} i.e. a voltage that can be directly converted into true requested object temperature.
U_{tot}	Measured camera output voltage for the actual case.
U_{refl}	Theoretical camera output voltage for a blackbody of temperature T_{refl} according to the calibration.
U_{atm}	Theoretical camera output voltage for a blackbody of temperature T_{atm} according to the calibration.

The operator has to supply a number of parameter values for the calculation:

- the object emittance ε,
- the relative humidity,
- T_{atm}
- object distance (D_{obj})
- the (effective) temperature of the object surroundings, or the reflected ambient temperature T_{refl}, and
- the temperature of the atmosphere T_{atm}

This task could sometimes be a heavy burden for the operator since there are normally no easy ways to find accurate values of emittance and atmospheric transmittance for the actual case. The two temperatures are normally less of a problem provided the surroundings do not contain large and intense radiation sources.

A natural question in this connection is: How important is it to know the right values of these parameters? It could though be of interest to get a feeling for this problem already here by looking into some different measurement cases and compare the relative magnitudes of the three radiation terms. This will give indications about when it is important to use correct values of which parameters.

The figures below illustrates the relative magnitudes of the three radiation contributions for three different object temperatures, two emittances, and two spectral ranges: SW and LW. Remaining parameters have the following fixed values:

- $\tau = 0.88$
- $T_{refl} = +20°C$ (+68°F)
- $T_{atm} = +20°C$ (+68°F)

It is obvious that measurement of low object temperatures are more critical than measuring high temperatures since the 'disturbing' radiation sources are relatively much stronger in the first case. Should also the object emittance be low, the situation would be still more difficult.

We have finally to answer a question about the importance of being allowed to use the calibration curve above the highest calibration point, what we call extrapolation. Imagine that we in a certain case measure U_{tot} = 4.5 volts. The highest calibration point for the camera was in the order of 4.1 volts, a value unknown to the operator. Thus, even if the object happened to be a blackbody, i.e. $U_{obj} = U_{tot}$, we are actually performing extrapolation of the calibration curve when converting 4.5 volts into temperature.

Let us now assume that the object is not black, it has an emittance of 0.75, and the transmittance is 0.92. We also assume that the two second terms of Equation 4 amount to 0.5 volts together. Computation of U_{obj} by means of Equation 4 then results in U_{obj} = 4.5 / 0.75 / 0.92 – 0.5 = 6.0. This is a rather extreme extrapolation, particularly when considering that the video amplifier might limit the output to 5 volts! Note, though, that the application of the calibration curve is a theoretical procedure where no electronic or other limitations exist. We trust that if there had been no signal limitations in the camera, and if it had been calibrated far beyond 5 volts, the resulting curve would have been very much the same as our real curve extrapolated beyond 4.1 volts, provided the calibration algorithm is based on radiation physics, like the FLIR Systems algorithm. Of course there must be a limit to such extrapolations.

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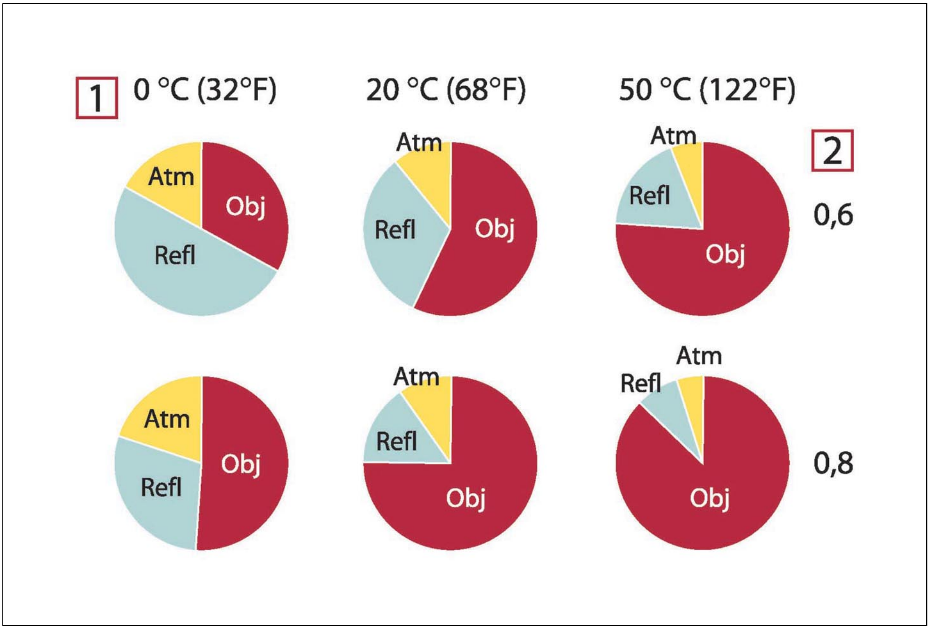

Figure 19.3 Relative magnitudes of radiation sources under varying measurement conditions (SW camera). **1:** Object temperature; **2:** Emittance; **Obj:** Object radiation; **Refl:** Reflected radiation; **Atm:** atmosphere radiation. Fixed parameters: $\tau = 0.88$; $T_{refl} = 20°C$ (+68°F); $T_{atm} = 20°C$ (+68°F).

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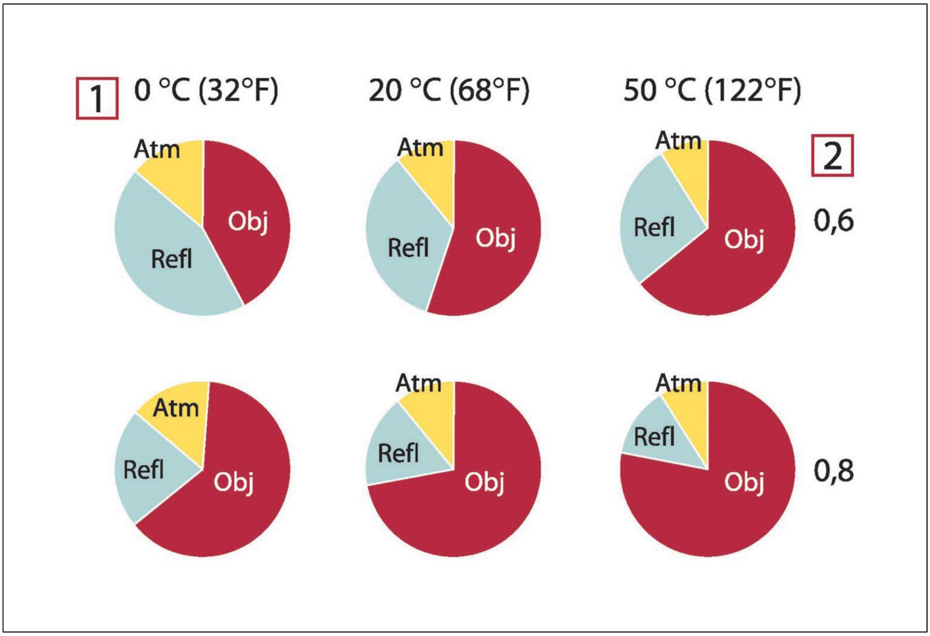

Figure 19.4 Relative magnitudes of radiation sources under varying measurement conditions (LW camera). **1:** Object temperature; **2:** Emittance; **Obj:** Object radiation; **Refl:** Reflected radiation; **Atm:** atmosphere radiation. Fixed parameters: $\tau = 0.88$; $T_{refl} = 20°C$ (+68°F); $T_{atm} = 20°C$ (+68°F).

20 Emissivity tables

This section presents a compilation of emissivity data from the infrared literature and measurements made by FLIR Systems.

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20.2 Important note about the emissivity tables

The emissivity values in the table below are recorded using a shortwave (SW) camera. The values should be regarded as recommendations only and used by caution.

20.3 Tables

Figure 20.1 **T:** Total spectrum; **SW:** 2–5 μm; **LW:** 8–14 μm, **LLW:** 6.5–20 μm; **1:** Material; **2:** Specification; **3:** Temperature in °C; **4:** Spectrum; **5:** Emissivity: **6:** Reference

1	2	3	4	5	6
3M type 35	Vinyl electrical tape (several colors)	< 80	LW	Ca. 0.96	13
3M type 88	Black vinyl electrical tape	< 105	LW	Ca. 0.96	13
3M type 88	Black vinyl electrical tape	< 105	MW	< 0.96	13
3M type Super 33+	Black vinyl electrical tape	< 80	LW	Ca. 0.96	13
Aluminum	anodized, black, dull	70	LW	0.95	9
Aluminum	anodized, black, dull	70	SW	0.67	9
Aluminum	anodized, light gray, dull	70	LW	0.97	9
Aluminum	anodized, light gray, dull	70	SW	0.61	9
Aluminum	anodized sheet	100	T	0.55	2
Aluminum	as received, plate	100	T	0.09	4
Aluminum	as received, sheet	100	T	0.09	2
Aluminum	cast, blast cleaned	70	LW	0.46	9
Aluminum	cast, blast cleaned	70	SW	0.47	9
Aluminum	dipped in HNO_3, plate	100	T	0.05	4
Aluminum	foil	27	3 μm	0.09	3
Aluminum	foil	27	10 μm	0.04	3
Aluminum	oxidized, strongly	50–500	T	0.2–0.3	1
Aluminum	polished	50–100	T	0.04–0.06	1
Aluminum	polished, sheet	100	T	0.05	2
Aluminum	polished plate	100	T	0.05	4

1	2	3	4	5	6
Aluminum	roughened	27	3 μm	0.28	3
Aluminum	roughened	27	10 μm	0.18	3
Aluminum	rough surface	20–50	T	0.06–0.07	1
Aluminum	sheet, 4 samples differently scratched	70	LW	0.03–0.06	9
Aluminum	sheet, 4 samples differently scratched	70	SW	0.05–0.08	9
Aluminum	vacuum deposited	20	T	0.04	2
Aluminum	weathered, heavily	17	SW	0.83–0.94	5
Aluminum bronze		20	T	0.60	1
Aluminum hydroxide	powder		T	0.28	1
Aluminum oxide	activated, powder		T	0.46	1
Aluminum oxide	pure, powder (alumina)		T	0.16	1
Asbestos	board	20	T	0.96	1
Asbestos	fabric		T	0.78	1
Asbestos	floor tile	35	SW	0.94	7
Asbestos	paper	40–400	T	0.93–0.95	1
Asbestos	powder		T	0.40–0.60	1
Asbestos	slate	20	T	0.96	1
Asphalt paving		4	LLW	0.967	8
Brass	dull, tarnished	20–350	T	0.22	1
Brass	oxidized	70	SW	0.04–0.09	9
Brass	oxidized	70	LW	0.03–0.07	9
Brass	oxidized	100	T	0.61	2
Brass	oxidized at 600°C	200–600	T	0.59–0.61	1
Brass	polished	200	T	0.03	1
Brass	polished, highly	100	T	0.03	2

1	2	3	4	5	6
Brass	rubbed with 80-grit emery	20	T	0.20	2
Brass	sheet, rolled	20	T	0.06	1
Brass	sheet, worked with emery	20	T	0.2	1
Brick	alumina	17	SW	0.68	5
Brick	common	17	SW	0.86–0.81	5
Brick	Dinas silica, glazed, rough	1100	T	0.85	1
Brick	Dinas silica, refractory	1000	T	0.66	1
Brick	Dinas silica, unglazed, rough	1000	T	0.80	1
Brick	firebrick	17	SW	0.68	5
Brick	fireclay	20	T	0.85	1
Brick	fireclay	1000	T	0.75	1
Brick	fireclay	1200	T	0.59	1
Brick	masonry	35	SW	0.94	7
Brick	masonry, plastered	20	T	0.94	1
Brick	red, common	20	T	0.93	2
Brick	red, rough	20	T	0.88–0.93	1
Brick	refractory, corundum	1000	T	0.46	1
Brick	refractory, magnesite	1000–1300	T	0.38	1
Brick	refractory, strongly radiating	500–1000	T	0.8–0.9	1
Brick	refractory, weakly radiating	500–1000	T	0.65–0.75	1
Brick	silica, 95% SiO_2	1230	T	0.66	1
Brick	sillimanite, 33% SiO_2, 64% Al_2O_3	1500	T	0.29	1

1	2	3	4	5	6
Brick	waterproof	17	SW	0.87	5
Bronze	phosphor bronze	70	LW	0.06	9
Bronze	phosphor bronze	70	SW	0.08	9
Bronze	polished	50	T	0.1	1
Bronze	porous, rough	50–150	T	0.55	1
Bronze	powder		T	0.76–0.80	1
Carbon	candle soot	20	T	0.95	2
Carbon	charcoal powder		T	0.96	1
Carbon	graphite, filed surface	20	T	0.98	2
Carbon	graphite powder		T	0.97	1
Carbon	lampblack	20–400	T	0.95–0.97	1
Chipboard	untreated	20	SW	0.90	6
Chromium	polished	50	T	0.10	1
Chromium	polished	500–1000	T	0.28–0.38	1
Clay	fired	70	T	0.91	1
Cloth	black	20	T	0.98	1
Concrete		20	T	0.92	2
Concrete	dry	36	SW	0.95	7
Concrete	rough	17	SW	0.97	5
Concrete	walkway	5	LLW	0.974	8
Copper	commercial, burnished	20	T	0.07	1
Copper	electrolytic, carefully polished	80	T	0.018	1
Copper	electrolytic, polished	–34	T	0.006	4
Copper	molten	1100–1300	T	0.13–0.15	1
Copper	oxidized	50	T	0.6–0.7	1
Copper	oxidized, black	27	T	0.78	4

1	2	3	4	5	6
Copper	oxidized, heavily	20	T	0.78	2
Copper	oxidized to blackness		T	0.88	1
Copper	polished	50–100	T	0.02	1
Copper	polished	100	T	0.03	2
Copper	polished, commercial	27	T	0.03	4
Copper	polished, mechanical	22	T	0.015	4
Copper	pure, carefully prepared surface	22	T	0.008	4
Copper	scraped	27	T	0.07	4
Copper dioxide	powder		T	0.84	1
Copper oxide	red, powder		T	0.70	1
Ebonite			T	0.89	1
Emery	coarse	80	T	0.85	1
Enamel		20	T	0.9	1
Enamel	lacquer	20	T	0.85–0.95	1
Fiber board	hard, untreated	20	SW	0.85	6
Fiber board	masonite	70	LW	0.88	9
Fiber board	masonite	70	SW	0.75	9
Fiber board	particle board	70	LW	0.89	9
Fiber board	particle board	70	SW	0.77	9
Fiber board	porous, untreated	20	SW	0.85	6
Gold	polished	130	T	0.018	1
Gold	polished, carefully	200–600	T	0.02–0.03	1
Gold	polished, highly	100	T	0.02	2
Granite	polished	20	LLW	0.849	8
Granite	rough	21	LLW	0.879	8
Granite	rough, 4 different samples	70	LW	0.77–0.87	9

1	2	3	4	5	6
Granite	rough, 4 different samples	70	SW	0.95–0.97	9
Gypsum		20	T	0.8–0.9	1
Ice: See Water					
Iron, cast	casting	50	T	0.81	1
Iron, cast	ingots	1000	T	0.95	1
Iron, cast	liquid	1300	T	0.28	1
Iron, cast	machined	800–1000	T	0.60–0.70	1
Iron, cast	oxidized	38	T	0.63	4
Iron, cast	oxidized	100	T	0.64	2
Iron, cast	oxidized	260	T	0.66	4
Iron, cast	oxidized	538	T	0.76	4
Iron, cast	oxidized at 600°C	200–600	T	0.64–0.78	1
Iron, cast	polished	38	T	0.21	4
Iron, cast	polished	40	T	0.21	2
Iron, cast	polished	200	T	0.21	1
Iron, cast	unworked	900–1100	T	0.87–0.95	1
Iron and steel	cold rolled	70	LW	0.09	9
Iron and steel	cold rolled	70	SW	0.20	9
Iron and steel	covered with red rust	20	T	0.61–0.85	1
Iron and steel	electrolytic	22	T	0.05	4
Iron and steel	electrolytic	100	T	0.05	4
Iron and steel	electrolytic	260	T	0.07	4
Iron and steel	electrolytic, carefully polished	175–225	T	0.05–0.06	1
Iron and steel	freshly worked with emery	20	T	0.24	1
Iron and steel	ground sheet	950–1100	T	0.55–0.61	1
Iron and steel	heavily rusted sheet	20	T	0.69	2

1	2	3	4	5	6
Iron and steel	hot rolled	20	T	0.77	1
Iron and steel	hot rolled	130	T	0.60	1
Iron and steel	oxidized	100	T	0.74	1
Iron and steel	oxidized	100	T	0.74	4
Iron and steel	oxidized	125–525	T	0.78–0.82	1
Iron and steel	oxidized	200	T	0.79	2
Iron and steel	oxidized	1227	T	0.89	4
Iron and steel	oxidized	200–600	T	0.80	1
Iron and steel	oxidized strongly	50	T	0.88	1
Iron and steel	oxidized strongly	500	T	0.98	1
Iron and steel	polished	100	T	0.07	2
Iron and steel	polished	400–1000	T	0.14–0.38	1
Iron and steel	polished sheet	750–1050	T	0.52–0.56	1
Iron and steel	rolled, freshly	20	T	0.24	1
Iron and steel	rolled sheet	50	T	0.56	1
Iron and steel	rough, plane surface	50	T	0.95–0.98	1
Iron and steel	rusted, heavily	17	SW	0.96	5
Iron and steel	rusted red, sheet	22	T	0.69	4
Iron and steel	rusty, red	20	T	0.69	1
Iron and steel	shiny, etched	150	T	0.16	1
Iron and steel	shiny oxide layer, sheet,	20	T	0.82	1
Iron and steel	wrought, carefully polished	40–250	T	0.28	1
Iron galvanized	heavily oxidized	70	LW	0.85	9
Iron galvanized	heavily oxidized	70	SW	0.64	9
Iron galvanized	sheet	92	T	0.07	4
Iron galvanized	sheet, burnished	30	T	0.23	1
Iron galvanized	sheet, oxidized	20	T	0.28	1

1	2	3	4	5	6
Iron tinned	sheet	24	T	0.064	4
Krylon Ultra-flat black 1602	Flat black	Room temperature up to 175	LW	Ca. 0.96	12
Krylon Ultra-flat black 1602	Flat black	Room temperature up to 175	MW	Ca. 0.97	12
Lacquer	3 colors sprayed on Aluminum	70	LW	0.92–0.94	9
Lacquer	3 colors sprayed on Aluminum	70	SW	0.50–0.53	9
Lacquer	Aluminum on rough surface	20	T	0.4	1
Lacquer	bakelite	80	T	0.83	1
Lacquer	black, dull	40–100	T	0.96–0.98	1
Lacquer	black, matte	100	T	0.97	2
Lacquer	black, shiny, sprayed on iron	20	T	0.87	1
Lacquer	heat–resistant	100	T	0.92	1
Lacquer	white	40–100	T	0.8–0.95	1
Lacquer	white	100	T	0.92	2
Lead	oxidized, gray	20	T	0.28	1
Lead	oxidized, gray	22	T	0.28	4
Lead	oxidized at 200°C	200	T	0.63	1
Lead	shiny	250	T	0.08	1
Lead	unoxidized, polished	100	T	0.05	4
Lead red		100	T	0.93	4
Lead red, powder		100	T	0.93	1
Leather	tanned		T	0.75–0.80	1
Lime			T	0.3–0.4	1
Magnesium		22	T	0.07	4
Magnesium		260	T	0.13	4

1	2	3	4	5	6
Magnesium		538	T	0.18	4
Magnesium	polished	20	T	0.07	2
Magnesium powder			T	0.86	1
Molybdenum		600–1000	T	0.08–0.13	1
Molybdenum		1500–2200	T	0.19–0.26	1
Molybdenum	filament	700–2500	T	0.1–0.3	1
Mortar		17	SW	0.87	5
Mortar	dry	36	SW	0.94	7
Nextel Velvet 811-21 Black	Flat black	–60–150	LW	> 0.97	10 and 11
Nichrome	rolled	700	T	0.25	1
Nichrome	sandblasted	700	T	0.70	1
Nichrome	wire, clean	50	T	0.65	1
Nichrome	wire, clean	500–1000	T	0.71–0.79	1
Nichrome	wire, oxidized	50–500	T	0.95–0.98	1
Nickel	bright matte	122	T	0.041	4
Nickel	commercially pure, polished	100	T	0.045	1
Nickel	commercially pure, polished	200–400	T	0.07–0.09	1
Nickel	electrolytic	22	T	0.04	4
Nickel	electrolytic	38	T	0.06	4
Nickel	electrolytic	260	T	0.07	4
Nickel	electrolytic	538	T	0.10	4
Nickel	electroplated, polished	20	T	0.05	2
Nickel	electroplated on iron, polished	22	T	0.045	4
Nickel	electroplated on iron, unpolished	20	T	0.11–0.40	1

1	2	3	4	5	6
Nickel	electroplated on iron, unpolished	22	T	0.11	4
Nickel	oxidized	200	T	0.37	2
Nickel	oxidized	227	T	0.37	4
Nickel	oxidized	1227	T	0.85	4
Nickel	oxidized at 600°C	200–600	T	0.37–0.48	1
Nickel	polished	122	T	0.045	4
Nickel	wire	200–1000	T	0.1–0.2	1
Nickel oxide		500–650	T	0.52–0.59	1
Nickel oxide		1000–1250	T	0.75–0.86	1
Oil, lubricating	0.025 mm film	20	T	0.27	2
Oil, lubricating	0.050 mm film	20	T	0.46	2
Oil, lubricating	0.125 mm film	20	T	0.72	2
Oil, lubricating	film on Ni base: Ni base only	20	T	0.05	2
Oil, lubricating	thick coating	20	T	0.82	2
Paint	8 different colors and qualities	70	LW	0.92–0.94	9
Paint	8 different colors and qualities	70	SW	0.88–0.96	9
Paint	Aluminum, various ages	50–100	T	0.27–0.67	1
Paint	cadmium yellow		T	0.28–0.33	1
Paint	chrome green		T	0.65–0.70	1
Paint	cobalt blue		T	0.7–0.8	1
Paint	oil	17	SW	0.87	5
Paint	oil, black flat	20	SW	0.94	6
Paint	oil, black gloss	20	SW	0.92	6
Paint	oil, gray flat	20	SW	0.97	6
Paint	oil, gray gloss	20	SW	0.96	6
Paint	oil, various colors	100	T	0.92–0.96	1

1	2	3	4	5	6
Paint	oil based, average of 16 colors	100	T	0.94	2
Paint	plastic, black	20	SW	0.95	6
Paint	plastic, white	20	SW	0.84	6
Paper	4 different colors	70	LW	0.92–0.94	9
Paper	4 different colors	70	SW	0.68–0.74	9
Paper	black		T	0.90	1
Paper	black, dull		T	0.94	1
Paper	black, dull	70	LW	0.89	9
Paper	black, dull	70	SW	0.86	9
Paper	blue, dark		T	0.84	1
Paper	coated with black lacquer		T	0.93	1
Paper	green		T	0.85	1
Paper	red		T	0.76	1
Paper	white	20	T	0.7–0.9	1
Paper	white, 3 different glosses	70	LW	0.88–0.90	9
Paper	white, 3 different glosses	70	SW	0.76–0.78	9
Paper	white bond	20	T	0.93	2
Paper	yellow		T	0.72	1
Plaster		17	SW	0.86	5
Plaster	plasterboard, untreated	20	SW	0.90	6
Plaster	rough coat	20	T	0.91	2
Plastic	glass fibre laminate (printed circ. board)	70	LW	0.91	9
Plastic	glass fibre laminate (printed circ. board)	70	SW	0.94	9

1	2	3	4	5	6
Plastic	polyurethane isolation board	70	LW	0.55	9
Plastic	polyurethane isolation board	70	SW	0.29	9
Plastic	PVC, plastic floor, dull, structured	70	LW	0.93	9
Plastic	PVC, plastic floor, dull, structured	70	SW	0.94	9
Platinum		17	T	0.016	4
Platinum		22	T	0.03	4
Platinum		100	T	0.05	4
Platinum		260	T	0.06	4
Platinum		538	T	0.10	4
Platinum		1000–1500	T	0.14–0.18	1
Platinum		1094	T	0.18	4
Platinum	pure, polished	200–600	T	0.05–0.10	1
Platinum	ribbon	900–1100	T	0.12–0.17	1
Platinum	wire	50–200	T	0.06–0.07	1
Platinum	wire	500–1000	T	0.10–0.16	1
Platinum	wire	1400	T	0.18	1
Porcelain	glazed	20	T	0.92	1
Porcelain	white, shiny		T	0.70–0.75	1
Rubber	hard	20	T	0.95	1
Rubber	soft, gray, rough	20	T	0.95	1
Sand			T	0.60	1
Sand		20	T	0.90	2
Sandstone	polished	19	LLW	0.909	8
Sandstone	rough	19	LLW	0.935	8
Silver	polished	100	T	0.03	2
Silver	pure, polished	200–600	T	0.02–0.03	1

1	2	3	4	5	6
Skin	human	32	T	0.98	2
Slag	boiler	0–100	T	0.97–0.93	1
Slag	boiler	200–500	T	0.89–0.78	1
Slag	boiler	600–1200	T	0.76–0.70	1
Slag	boiler	1400–1800	T	0.69–0.67	1
Snow: See Water					
Soil	dry	20	T	0.92	2
Soil	saturated with water	20	T	0.95	2
Stainless steel	alloy, 8% Ni, 18% Cr	500	T	0.35	1
Stainless steel	rolled	700	T	0.45	1
Stainless steel	sandblasted	700	T	0.70	1
Stainless steel	sheet, polished	70	LW	0.14	9
Stainless steel	sheet, polished	70	SW	0.18	9
Stainless steel	sheet, untreated, somewhat scratched	70	LW	0.28	9
Stainless steel	sheet, untreated, somewhat scratched	70	SW	0.30	9
Stainless steel	type 18-8, buffed	20	T	0.16	2
Stainless steel	type 18-8, oxidized at 800°C	60	T	0.85	2
Stucco	rough, lime	10–90	T	0.91	1
Styrofoam	insulation	37	SW	0.60	7
Tar			T	0.79–0.84	1
Tar	paper	20	T	0.91–0.93	1
Tile	glazed	17	SW	0.94	5
Tin	burnished	20–50	T	0.04–0.06	1
Tin	tin–plated sheet iron	100	T	0.07	2

1	2	3	4	5	6
Titanium	oxidized at 540°C	200	T	0.40	1
Titanium	oxidized at 540°C	500	T	0.50	1
Titanium	oxidized at 540°C	1000	T	0.60	1
Titanium	polished	200	T	0.15	1
Titanium	polished	500	T	0.20	1
Titanium	polished	1000	T	0.36	1
Tungsten		200	T	0.05	1
Tungsten		600–1000	T	0.1–0.16	1
Tungsten		1500–2200	T	0.24–0.31	1
Tungsten	filament	3300	T	0.39	1
Varnish	flat	20	SW	0.93	6
Varnish	on oak parquet floor	70	LW	0.90–0.93	9
Varnish	on oak parquet floor	70	SW	0.90	9
Wallpaper	slight pattern, light gray	20	SW	0.85	6
Wallpaper	slight pattern, red	20	SW	0.90	6
Water	distilled	20	T	0.96	2
Water	frost crystals	–10	T	0.98	2
Water	ice, covered with heavy frost	0	T	0.98	1
Water	ice, smooth	–10	T	0.96	2
Water	ice, smooth	0	T	0.97	1
Water	layer >0.1 mm thick	0–100	T	0.95–0.98	1
Water	snow		T	0.8	1
Water	snow	–10	T	0.85	2
Wood		17	SW	0.98	5
Wood		19	LLW	0.962	8
Wood	ground		T	0.5–0.7	1

1	**2**	**3**	**4**	**5**	**6**
Wood	pine, 4 different samples	70	LW	0.81–0.89	9
Wood	pine, 4 different samples	70	SW	0.67–0.75	9
Wood	planed	20	T	0.8–0.9	1
Wood	planed oak	20	T	0.90	2
Wood	planed oak	70	LW	0.88	9
Wood	planed oak	70	SW	0.77	9
Wood	plywood, smooth, dry	36	SW	0.82	7
Wood	plywood, untreat-ed	20	SW	0.83	6
Wood	white, damp	20	T	0.7–0.8	1
Zinc	oxidized at 400°C	400	T	0.11	1
Zinc	oxidized surface	1000–1200	T	0.50–0.60	1
Zinc	polished	200–300	T	0.04–0.05	1
Zinc	sheet	50	T	0.20	1

A note on the technical production of this manual

This manual was produced using XML—the *eXtensible Markup Language*. For more information about XML, please visit http://www.w3.org/XML/

A note on the typeface used in this manual

This manual was typeset using Swiss 721, which is Bitstream's pan-European version of the Helvetica™ typeface. Helvetica™ was designed by Max Miedinger (1910–1980).

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20238503.xml a9
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20250403.xml a17
20254903.xml a57
20257003.xml a33
20275203.xml a12
20287303.xml a7
20290503.xml a7
20290603.xml a7
20290703.xml a10
20290903.xml a7
20291003.xml a7
20291103.xml a9
20291203.xml a6
20291303.xml a6
20291403.xml a2
20291603.xml a2
20292403.xml a4
R116.rcp a3
config.xml a5

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